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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(54) Title: ACTIVE STRUCTURAL CONTROL SYSTEM AND METHOD INCLUDING ACTIVE VIBRATION ABSORBERS (AVAs)

(57) Abstract

An Active Structural Control (ASC) system (10) and method which includes a plurality of Active Vibration Absorbers (AVAs) (40) attached to a yoke (32) included within a pylon structure (28) preferably comprising a spar (38) and a yoke (32) which is located intermediate between an aircraft fuselage (20) and an aircraft engine (18) for controlling acoustic noise and/or vibration generated within the aircraft's cabin (44) due to unbalances in the aircraft engine (18). The ASC system (10) includes a plurality of error sensors (42 or 63) for providing error signals, and at least one reference sensor (49 or 50) for providing reference signals indicative of the N1 and/or N2 engine rotations and/or vibrations, and a preferably digital electronic controller (46) for processing the error and reference signal information to provide output signals to dynamically vibrate the plurality of AVAs (40) attached to the yoke (32). The AVAs (40) preferably act in a radial, tangential, or fore and aft directions and may be located at the terminal end and/or at the base portion of the yoke (32). Further, the AVAs (40) may be Single Degree Of Freedom (SDOF) or Multiple Degree Of Freedom (MDOF) and may be tuned to have a passive resonance which substantially coincides with the N1 and/or N2 engine rotation and/or vibrations. In another aspect, reference signal processing is described which includes a modulo counter, a lookup table, and a digital IO device.
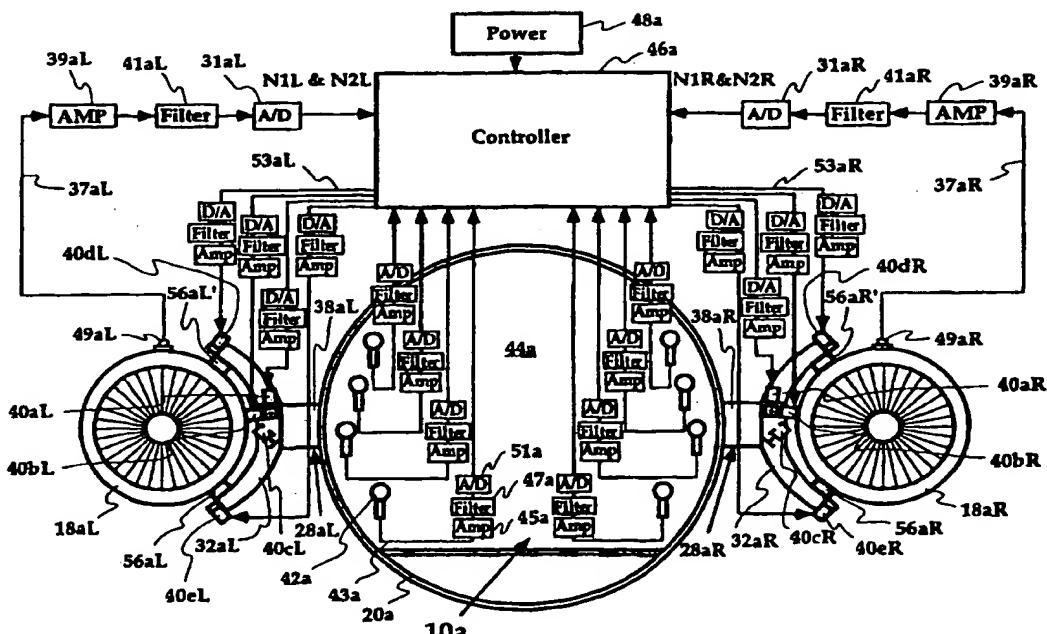
ACTIVE STRUCTURAL CONTROL SYSTEM AND METHOD INCLUDING ACTIVE VIBRATION ABSORBERS (AVAs)

Field of the Invention

This invention relates to the area of systems and methods for
5   controlling acoustic noise and vibration within an aircraft's cabin.
Specifically, it relates to actively-controlled devices and methods for
controlling noise and vibration via Active Structural Control (ASC) methods.

Background of the Invention

Irritating and annoying acoustic noise and dynamic vibration can be
10   created within an aircraft's cabin due to rotational unbalances and the like of
the aircraft's engine(s). For example, on fuselage-mounted aircraft engines,
the rotational unbalance(s) cause vibration to be transmitted into the yoke
structure, through the intermediate spar structure, and into the aircraft's
fuselage. If the vibration of the fuselage is well coupled to the acoustic space
15   within the aircraft's cabin, then annoying, predominantly tonal sound
(generally characterized as a low frequency irritating drone) can be generated
therewithin. In particular, this drone generally corresponds with the most
dominant engine tones, for example, the tones created via the N1 and N2
engine rotations. In aircraft with aft-fuselage-mounted engines, such as the
20   McDonnell Douglas DC-9 aircraft, any rotational unbalance of the engines
may result in unwanted and annoying low frequency noise being generated
within the aircraft's cabin, and specifically in the aft portion thereof. In
general, passengers in the aft portion of the cabin experience this low-
frequency tonal noise (drone) related to the N1 and N2 tones of the engine.
25   The N1 and N2 tones are generated by rotational unbalances of the turbine
(fan) and compressor stages (compressor) of attached multistage jet engines.
Elimination of the N1 and N2 tones can dramatically reduce the discomfort

experienced by the passengers, particularly in the aft-most portion of the aircraft's cabin.

Within the prior art, various means have been employed to counter aircraft cabin acoustic noise. These include passive blankets, passive Tuned
5   Vibration Absorbers (TVAs), adaptive TVAs, Active Noise Control (ANC), Active Structural Control (ASC), and Active Isolation Control (AIC). Passive blankets are generally effective in attenuating higher-frequency noise, but are generally ineffective at attenuating low-frequency noise of the type described herein, i.e., low-frequency drone. Furthermore, passive blankets must be
10   massive to reduce low-frequency noise transmission into the cabin. Passive Tuned Vibration Absorbers (TVAs) may be effective at attenuating low-frequency noise, but are generally limited in range and effectiveness. Passive TVAs include a suspended mass which is tuned (along with a stiffness) such that the device exhibits a resonant natural frequency (fn) which generally
15   cancels or absorbs vibration of the vibrating member at the point of attachment thereto. The afore-mentioned disadvantage of passive TVAs is that they are only effective at a particular frequency (fn) or within a very narrow frequency range thereabouts. Therefore, TVAs may be ineffective if the engine frequency is changed and the TVA is not operating at its resonant
20   frequency. Furthermore, passive devices may be unable to generate the proper magnitude and phasing of forces needed for effective vibration suppression and/or control. Passive TVAs are generally attached to the interior stiffening rings or stringers of the fuselage or to the yoke. US Pat. No. 3,490,556 to Bennett, Jr. et al. entitled: "Aircraft Noise Reduction System With
25   Tuned Vibration Absorbers" describes a passive vibration dampening device for use on the pylon of an aircraft for absorbing vibration at the N1 and N2 rotational frequencies.

When a wider range of vibration cancellation is required, various adaptive TVAs may be employed. For example, US Pat. No. 3,487,888 to
30   Adams et al. entitled "Cabin Engine Sound Suppresser" teaches an adaptive

TVA where the resonant frequency (fn) can be adaptively adjusted by changing the length of the beam or the rigidity of a resilient cushioning material. Although, the range of vibration attenuation may be increased with adaptive TVAs, they still may be ineffective for certain applications, in that their range of adjustment may not be large enough or they may not be able to generate enough dynamic forces to adequately reduce acoustic noise or vibration experienced within the aircraft's cabin.

In some applications where a higher level of noise attenuation is desired, Active Isolation Control (AIC) systems provide another means for controlling noise within an aircraft's cabin. In **Prior Art Fig. 1**, an aircraft with multiple aft-fuselage-mounted turbofan engines is shown. AIC systems include active mountings, such as 12a, 12b, 12c, and 12d, which include an actively driven element contained therein, to provide the active control forces for isolating vibration and preventing its transmission from the engines 18L and 18R into the pylon structures 28L and 28R. The resultant effect is preferably a reduction of annoying interior acoustic noise in the aircraft's cabin 44. Known AIC systems include the feedforward type, in that reference signals, such as from reference accelerometers 49L and 49R, are used to provide a reference signal indicative of the N1 and N2 vibrations of engines, 18L and 18R. Error sensors, such as a plurality of microphones 42, provide error signals indicative of the residual noise at various locations in the aircraft cabin 44. Specifically, in known AIC systems, active mountings, such as 12a-d are attached between an aircraft yoke 32L and 32R and the aircraft's engine 18L and 18R. The reference signals and error microphones 42 are processed by a digital controller 46 to generate drive signals of the appropriate phase and magnitude (anti-vibration) to reduce vibration transmission from the engine to the yoke, and resultantly controlling and/or reducing the interior acoustic noise.

Copending US Patent Application Serial Number 08/260,945 entitled "Active Mounts For Aircraft Engines" describes several AIC systems.

Furthermore, commonly assigned US Pat. No. 5,174,552 to Hodgson et al. entitled "Fluid Mount With Active Vibration Control" describes the details of one type of active fluid mounting. It should be understood, that in some applications, there may be insufficient space envelope to incorporate the

5   active element within the active mounting. Furthermore, there may be alternate vibration paths into the structure or the appropriate actuation directions required for vibration attenuation may be difficult to accomplish within the environment of an active mounting. Furthermore, modification to the mounting system, to incorporate active elements may reduce the

10   amount of load bearing surface, possibly reducing the drift-life expectancy of the mounting system.

Active Noise Control (ANC) systems are also well known. As described with reference to Prior Art Fig. 2, ANC systems may be used on turboprop aircraft or the like, and include a plurality of acoustic output

15   transducers, such as loudspeakers 16a, 16b, 16c, and 16d, strategically located within the aircraft's cabin 44 and attached to the aircraft's trim. These loudspeakers are driven responsive to input signals from input sensors and error signals from error sensors 42 disbursed within the aircraft's cabin 44. Input signals may be derived from engine tachometers, accelerometers, or the

20   like, which are placed on the engines 18L and 18R, or reference sensors 14L and 14R located on the fuselage in the area of the aerodynamic propeller wash generated by the propellers 17L and 17R driven by engines 18L and 18R mounted on wings 15L and 15R. The output signals to the loudspeakers 16a-16d, in ANC systems are generally adaptively controlled via a digital

25   controller 46 according to a known feedforward type adaptive control algorithm, such as the Filtered-x Least Mean Square (LMS) algorithm, or the like. Copending US patent application Serial Number 08/553,227 to Billoud entitled "Active Noise Control System For Closed Spaces Such As Aircraft Cabins" describes one such ANC system. ANC systems have the

30   disadvantage that they do not generally address any mechanical vibration problems and may be difficult to retrofit to existing aircraft. Furthermore, as

the frequency of noise increases, large numbers of error sensors and speakers are required to achieve sufficient global noise attenuation.

Certain ASC systems, known in the prior art, may solve this problem of needing a large number of error sensors by attacking the vibrational modes of the aircraft's fuselage directly. For example, by attaching "a vibrating device such as an actuator or a shaker which is directly connected to the *interior surface* of the fuselage in order to introduce a vibration directly into the fuselage surface", as described in US Pat. No. 4,715,559 to Fuller, global attenuation can be achieved with a minimal number of error sensors. However, the modifications necessary to retrofit AVAs in this manner may be prohibitive, as the interior trim may have to be removed and structural modifications made have to be made to the stringers or stiffening-ring frames. Furthermore, for control of N2 tones, an exceedingly large number of AVAs may be needed. Therefore, prior art ASC systems are necessarily difficult to retrofit and may require the use of many shaker/actuators to effectuate control of higher-order tones. US Pat. No. 5,310,137 to Yoerkie, Jr. et al. describes the use of AVAs to cancel high-frequency vibrations of a helicopter transmission. Notably, Yoerkie, Jr. et al. is a feedback-type system.

Further descriptions of AVAs and active mounts can be found in Copending US application Serial Number 08/322,123 entitled "Active Tuned Vibration Absorber" and copending PCT application PCT/US95/13610 entitled "Active Systems and Devices Including Active Vibration Absorbers (AVAs)."

Therefore, there is a recognized need for an ASC system which provides active attenuation to effectively minimize vibration within the structure attached between the engine and the fuselage of an aircraft with the result of reducing annoying acoustic noise and mechanical vibration within the aircraft's cabin throughout its entire frequency range, and without the need for major modification of the fuselage or the aircraft engine mountings, thus allowing ease of retrofit of the system.

Summary of the Invention

Therefore, in light of the advantages and drawbacks of the prior art, the present invention is an Active Structural Control (ASC) system of the type useful for control of noise and/or vibration caused by aircraft engines, e.g., aft-fuselage-mounted turbofan engines. In the ASC system, vibration is controlled within a yoke structure of the aircraft which interconnects between the spar and aircraft engine. The yoke and spar comprise, in general, a pylon structure which interconnects between at least one aircraft engine and the aircraft's fuselage. The ASC system comprises a plurality of error sensors for providing a plurality of error signals representative of the residual noise or vibration, and in the case of the aft-fuselage-mounted engine, are preferably located at an aft-most portion of said aircraft cabin. At least one reference sensor associated with said at least one engine provides at least one reference signal selected from the group consisting of a first reference signal indicative of an N1 engine rotation and a second reference signal indicative of an N2 engine rotation. A plurality of Active Vibration Absorbers (AVAs) are attached to said yoke with various preferable orientations, and with preferable tuning to increase efficiency. A digital electronic controller is used for processing said at least one reference signal and said plurality of error signals according to a feedforward-adaptive algorithm, such as filtered-x Least Mean Square (LMS) to update weights within a plurality of control filters. The output from the plurality of control filters provide a plurality of output signals to said plurality of AVAs. The ensuing effect is control of vibration within said yoke, which resultantly controls acoustic noise and/or vibration within said aircraft's cabin.

It is an advantage that the present invention ASC system can be easily retrofitted to existing turbofan aircraft, in the field, without extensive modification thereto.

It is an advantage that the present invention ASC system can control vibration of the yoke over a wide frequency range, thereby controlling unwanted and annoying acoustic noise within the aircraft's cabin over a wide frequency range.

5   It is an advantage that the present invention ASC system can control acoustic noise within the aircraft's cabin throughout the engine's operational range.

It is an advantage that the present invention ASC system can generate larger dynamic forces than the prior art passive TVA systems.

10   It is an advantage that the present invention ASC system can adapt phase.

It is an advantage that the present invention ASC system can control both annoying N1 and N2 tones within the aft portion of the aircraft cabin.

It is an advantage that the present invention ASC system can control
15   the annoying acoustical beat between the engines.

It is an advantage that the present invention ASC system may minimize potentially metal fatigue producing vibration.

The abovementioned and further features, advantages, and characteristics of the present invention will become apparent from the
20   accompanying descriptions of the preferred and other embodiments and attached drawings.

25

Brief Description of the Drawings

The accompanying drawings which form a part of the specification, illustrate several key embodiments of the present invention. The drawings and description together, serve to fully explain the invention. In the drawings,

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Fig. 1 is a schematic forward-looking view of a prior art Active Isolation Control (AIC) system including active mountings attached between the engines and yokes,

10   Fig. 2 is a schematic forward-looking view of a prior art Active Noise Control (ANC) system including loudspeakers located within the cabin for producing anti-noise,

Fig. 3a is a schematic forward-looking view of a first embodiment of the present invention ASC system including multiple AVAs attached to the

15   yokes of an aircraft wherein reference signals are derived from accelerometer reference sensors,

Fig. 3b is a schematic forward-looking view of a second embodiment of the present invention ASC system including AVAs attached to the yoke of an aircraft wherein reference signals are derived from multiple tachometer

20   reference sensors,

Fig. 3c is a block diagram of the input, control, and output components related to driving one of the AVAs for controlling vibration of the right yoke in the Fig. 3a embodiment at multiple frequencies,

Fig. 3d is a block diagram of the input, control, and output components of the

25   Fig. 3b embodiment,

Fig. 3e is a further refined block diagram of one particular type of adaptive control useful for controlling the AVAs in the Fig. 3a embodiment,

Fig. 3f is a block diagram of one possible control filter configuration (e.g. FIR) which could be used with the **Fig. 3a or 3b** embodiment,

Fig. 3g is a block diagram of another possible adaptive control which could be used in the **Fig. 3a or 3b** embodiment,

5   Fig. 3h is a graphical plot illustrating the reductions of the N1R, N1L and N2R, N2L tones by the present invention ASC system including AVAs attached to the yoke as compared to a baseline system which includes only passive TVAs attached to the yoke,

Fig. 3i is a cross-sectioned side view of a SDOF AVA,

10 Fig. 3j is a cross-sectioned side view of a MDOF AVA,

Fig. 4a is a detailed partial forward-looking schematic view of the first embodiment of the present invention ASC system illustrating AVA locations/directions on the right yoke,

Fig. 4b is a detailed partial forward-looking schematic view of another
15 embodiment of the present invention ASC system illustrating preferred locations of accelerometer error sensors,

Fig. 5a is a schematic diagram of the first embodiment described with reference to **Fig. 3a** including reference accelerometer sensors and illustrating the preferred locations/directions of the plurality of AVAs on the yokes,

20 Fig. 5b is a schematic diagram of another embodiment illustrating locations/directions of a plurality of AVAs on the right yoke,

Fig. 5c is a schematic diagram of another embodiment illustrating preferred locations/directions of a plurality of AVAs,

Fig. 5d is a schematic diagram of another embodiment illustrating preferred
25 locations/directions of a plurality of AVAs,

Fig. 6a is a schematic block diagram of the Fig. 3a embodiment of the present invention ASC system,

Fig. 6b is a schematic block diagram of the Fig. 3b embodiment of the present invention ASC system,

5   Fig. 6c is a schematic block diagram of the third embodiment of the present invention ASC system described with reference to Fig. 4b,

Fig. 7a is a schematic block diagram of a ANVC system illustrating one implementation for deriving the input signal(s),

Fig. 7b and Fig. 7c illustrate the reference signal(s) at various points during the
10   conditioning process,

Fig. 7d illustrates the count versus the cycle, and

Fig. 7e illustrates a input signal lookup table.

Detailed Description of the Invention

Referring now to the Drawings where like numerals denote like
15   elements, in Fig. 3a, shown generally at 10a, is a first embodiment of the present invention Active Structural Control (ASC) system for controlling annoying acoustic noise and/or vibration generated within an aircraft's cabin 44a. This invention has particular applicability for aft-fuselage-mounted turbofan aircraft, such as the DC-9 aircraft including, by way of example, aft-
20   fuselage-mounted Pratt & Whitney JT8D engines. The noise and/or vibration in the cabin 44a result from vibration generated by a rotational unbalance or the like of at least one engine, and in this example, two aft-fuselage-mounted turbofan jet engines, 18aL and 18aR. The dynamic mechanical vibration is transmitted into the pylon structures, 28aL and 28aR, which are attached on
25   either side of the fuselage 20a. Each pylon structure 28aL and 28aR includes crescent-shaped yokes, 32aL and 32aR, and generally radially extending spars,

38aL and 38aR. Transmitted vibration from engines 18aL and 18aR cause vibration of the fuselage 20a.

Vibration of the fuselage and various passive means for controlling cabin noise therein are further described in AIAA paper No. 67-401 entitled "Cabin Noise Reduction in the DC-9 Aircraft" by J. VanDyke, Jr., J. Schendel, C. Gunderson, and M. Ballard. The vibration of the fuselage 20a generates irritating acoustic noise and/or vibration within said aircraft's cabin 44a with dominant tones that generally emerge at the N1 and N2 engine rotation frequencies. It was discovered by the inventors, that by the novel active control of the residual vibration within the yoke, 32aL and 32aR, the tonal noise generated by both the N1 low-speed rotor vibration and N2 high-speed rotor vibration of the engines 18aL and 18aR may both be reduced over their operating range. Higher-order tones (such as those coincident with 2N1) may also be controlled. In short, the invention herein described is an apparatus for actively controlling the vibration of the yokes 32aL and 32aR with the resultant effect of controlling unwanted noise and/or vibration occurring within the cabin 44a.

In particular, the noise reduction tracks changes in the engine(s) speed, thus, allowing for noise and vibration control/reductions over the wide range of frequencies associated with N1 and N2. Specifically, the noise associated with N1 and N2 can be as high as 110 dB, or more at N1 and N2 without active control. The present invention generally reduces the N1 and N2 tones down to the background noise (by as much as 20 dB or more, See Fig. 3h).

The ASC system 10a is comprised of a plurality of error sensors 42a, such as microphones shown, strategically arranged and equally spaced about the aircraft cabin 44a, and in particular, for the aft-fuselage-mounted engine case, the error sensors 42a are preferably only located in the aft portion (preferably the aft 1/2 portion - between the aft galley and the rear wing spar)

of the cabin 44a, for providing a plurality of error signals, via plurality of error cables 43a attached thereto, directly to the digital electronic controller 46a. It was discovered by the inventors that placing the plurality of error sensors 42a only in the aft portion in the aft-fuselage-mounted engine case, it was possible

5   to effectuate a reduction there, but also elsewhere in the cabin 44a. In this case, the error signals are representative of the residual acoustic noise within the aft portion of the aircraft cabin 44a at the location of each of the plurality of error sensors 42a. The error path includes amps 45a, filters 47a, and Analog-to-Digital (A/D) converters 51a. It should be understood that these

10 elements may be housed within the box/housing containing the controller, and are shown separately for clarity. The amps 45a amplify the error signal to appropriate levels and may include further conditioning. The filters 47a, such as a low pass filter, high pass filter, band pass filter, or combinations thereof, filter out signal portions outside the frequency range of control to

15 provide relatively noise-free error signals (containing only frequency information within the control frequency range). The A/D converter 51a converts the analog signal into a useable digital form to be processed in digital form by the digital electronic controller 46a. The error signals may be sampled at either a constant or variable sampling rate.

20   By way of example, eight error sensors 42a are shown in this cross-section of the fuselage 20a. The actual number n of error sensors 42a, preferably located in the aft-most portion of fuselage 20a, will vary by application. Generally, the number n of error sensors 42a will be selected based upon the number m of AVAs present in the system. It is generally

25 understood that the number of error sensors 42a should be equal to, or greater than, the number of AVAs. By way of example, and not by limitation, the preferred ASC system includes about 16 error microphones in the aft 1/2 portion of the aircraft cabin and about 8-12 AVAs (4-6 per engine). The error sensors 42a are preferably placed in a plane adjacent to the passengers' head

30 height or thereabouts on either side of the aircraft cabin. Optionally,

accelerometers may be used as the error sensors, as will be explained with reference to Fig. 4b.

In more detail, the ASC system 10a includes at least one reference sensor for providing a reference signal representative of the frequency (and possibly the magnitude) of the N1 and N2 engine vibrations/rotations for each engine 18aL and 18aR. For example, in this embodiment, two reference accelerometers, 49aL and 49aR, are provided, one on each engine 18aL and 18aR, for deriving a first reference signal indicative of an N1 engine vibration and a second reference signal indicative of an N2 engine vibration, for each engine 18aL and 18aR. Although, shown with one sensor 49aL and 49aR providing both N1 and N2 information for each engine 18aL and 18aR, it should be understood that separate sensors may provide the signal indicative of N1 and N2 vibration for each engine, 18aL and 18aR.

In this embodiment, the accelerometers 49aL and 49aR would preferably attach to the engine casings at an appropriate point such that each sensor 49aL and 49aR picks up and transmits the N1 and N2 vibrations for each respective engine 18aL and 18aR. The reference signals are provided via reference cables 37aL and 37aR, and in this embodiment, each signal includes vibrational contributions from N1 with superimposed N2 vibrations included thereon. The signals are amplified within input amps 39aL and 39aR to the appropriate voltage level, filtered by analog input filters 41aL and 41aR to filter out unwanted frequency information and prevent aliasing, and then input directly into input A/D converters 31aL and 31aR. The A/D converters preferably sample the analog signal at a constant sample rate of at least about 4 times the N2 frequency or approximately 1000 hz and, thereby, provide digital reference signals indicative of the N1 vibration and the N2 vibration to the controller 46a. Optionally, variable rate reference signal sampling could be employed. It should be understood that the input sampling and control filter update process are preferably asynchronous, in that they are not synchronized with the input signal and take place independent thereof.

However, synchronous sampling could also be employed as well as a synchronous control method. The input signals, once they are band separated and further conditioned to derive the N1 and N2 digital signals, are then processed digitally (convoluted) with control filters (preferably transversal

5   FIR filters) and summed to generate an output signal for each AVA. Transversal filters are described with reference to **Fig. 3e** and **Fig. 3f**.

Output signals in output cables such as **53aL** and **53aR** are provided to drive the plurality of Active Vibration Absorbers (AVAs) (**Figs. 3a, 4a** and **5a**). The AVAs are directly attached by way of brackets, e.g. **61aR, 61aR', 62aR,**

10   **62aR'** (**Fig. 4a**) to the right and left yokes, **32aL** and **32aR**. The number of transversal filters required, in the fully-coupled case, is generally equal to the number of tones being controlled, in this case both **N1** and **N2** tones are preferably controlled, times the number of engines, in this example two jet engines, **18aL** and **18aR**, and finally times the number of AVAs **42aL-42hL,**

15   **42aR-42hR** (in this case, preferably 6 AVAs per engine), or 2X2X12=48 control filters. It should be understood that the number of control filters required is preferably reduced   through reference sensor/signal partitioning and/or through error sensor partitioning to be described later.

The left and right yokes, **32aL** and **32aR**, attach directly to the left and

20   right spars, **38aL** and **38aR**, at the spars' terminal ends, whereas the other end of the spars, **38aL** and **38aR**, attaches directly to the fuselage **20a**. The left and right yokes, **32aL** and **32aR**, and left and right spars, **38aL** and **38aR**, make up and comprise the left and right pylon structures, **28aL** and **28aR**. What are referred to herein as the pylon structures, **28aL** and **28aR**, are located

25   intermediate and between the at least one engine, for example **18aL** and the aircraft's fuselage **20a**.

A preferably digital electronic controller **46a** processes said first reference signal(s) and said second reference signal(s) information and said plurality of error signals in an adaptive feedforward fashion and provides a

plurality of output signals to said plurality of active vibration absorbers e.g. 40aL-40hL, 40aR-40hR (Fig. 5a) to directly effectuate control of vibration within said yokes, 32aL and 32aR, and resultantly globally control acoustic noise generation and mechanical vibration emerging within said aircraft

5   cabin 44a, and specifically within the aft portion of the aircraft cabin 44a. N1L, N2L, N1R and N2R signals indicative of the vibration of engines 18aL and 18aR provide reference signals to the control process such that the acoustic noise coincident with the N1 and N2 tones of each engine 18aL and 18aR can be simultaneously controlled. The power 48a required to operate the ASC

10   system 10a is preferably derived from a main power bus or the aircraft. The ASC system 10b is preferably installed in combination with passive mounts 56aL, 56aL' and 56aR and 56aR' which are attached between the yokes 32aL and 32aR and the engines 18aL and 18aR. AVAs 40aL, 40bL, 40dL, 40eL and 40aR, 40bR, 40dR, 40eR are preferably devices which provide active forces

15   along a single linear axis only.

Fig. 3b illustrates another embodiment of ASC system 10b. This ASC system 10b is similar to that described with reference to Fig. 3a except that the input (reference) signal is derived from multiple tachometer sensors 50L, 50L', 50R, and 50R', two associated with each engine 18bL and 18bR.   For

20   example, sensor 50L and sensor 50R pick up signals indicative of N1L and N1R rotations of the left and right engines 18bL and 18bR, respectively.

The signal indicative of N1L and N1R (and also N2L and N2R) are actually signals indicative of a passage frequency of gear teeth members associated with the engine's fan assembly and must be adjusted by some

25   rational number (a Gear Ratio (GR)) to arrive at a signal exactly correlated with N1L and N1R, i.e., the exact N1L and N1R signals. First, the raw signal indicative of the gear tooth passage frequency is preferably converted into a square wave via hysteresis operation. The signal is then reduced (clipped) by limiter 55L to cut off the peaks of the signal to a finite voltage level. That

30   quasi-clipped signal in line 59L is fed into a Phase Locked Loop (PLL) 57L

which locks onto the dominant rotational frequency relating to the fan gear tooth passage frequency and preferably includes a multiplication factor (derived from a divide step in the comaparator path of the PLL). Next that signal output from the PLL **57L** in line **60L** is preferably divided via divider

5   **58L** by some integer multiple. By way of example, the N1L signal may be first multiplied in PLL **57L** by an integer number and divided in divider **58L** by an integer number. By way of example, the GR's for N1L and N2L are given by:

$$GR_{N1} = 47/23$$

$$GR_{N2} = 35/12$$

10   and N1L, N2L frequencies are given by:

N1L = GR_{N1} x Raw Signal at **59L**

N2L = GR_{N2} x Raw Signal at **59L'**

Likewise, the N2L signal is derived from tachometer sensor **50L'** which is limited by limiter **55L'**, passed through PLL **57L'** to provide a multiplied

15   signal in line **60L'**, and divided by divider **58L'** to provide the exact N2L signal. Similar limiters **55R** and **55R'**, PLLs **57R** and **57R'**, and dividers **58R** and **58R'** are provided for deriving the N1R and N2R signals. It should be recognized that if a one-to-one signal is available, then the divide step in the PLLs and the dividers are not needed.

20   All of the processing and memory storage operations relating to providing output signals to the AVAs is preferably accomplished within the digital electronic controller **46b**.

With reference to **Fig. 3c**, the input, output, and control components associated with driving a single AVA, such as AVA **40dR** located on right

25   yoke **32aR** (**Fig. 3a**) are described. Although, only the components for AVA **40dR** on the right yoke **32aR** are described, it should be understood that like elements would be associated with each of the other AVAs on the right yoke

32aR as well as all AVAs on the left yoke 32aL. An accelerometer 49aR provides the input signal indicative of N1R and N2R. That input signal is conditioned and amplified by input amp & conditioner 39aR. A/D converter 31aR transforms the signal into digital form. Box 70aR indicates the steps taking place within the digital controller 46a (Fig. 3a) and which preferably take place in software.

An optional digital prefiltering step including prefilter 25aR (digital low pass, high pass, band pass or combinations thereof) may be used to further refine the input signal. Next, the signal containing N1R and N2R components is separated into its N1R and N2R components using a digital band separation filter 27aR which may also comprise digital low pass, high pass, band pass filters, or combinations thereof. Preferably, a low pass is used to derive the N1R signal and a high pass is used to derive the N2R signal. The cutoff frequency for each is in between N1R and N2R. Optional ALEs 23aR and 23aR' can be included to further enhance/refine the N1R and N2R reference signals. ALEs are described in US Patent Application Serial Number 08/673,458 filed June 17, 1996 by Southward et al. entitled "Active Noise Or Vibration Control (ANVC) System And Method Including Enhanced Reference Signals."

Each signal indicative of N1R and N2R is convolved with the appropriate control filter within a N1R control filter block 21aR and with the appropriate control filter within a N2R control filter block 21aR', respectively, to produce individual control filter output signals at the N1R and N2R frequencies. The blocks of control filters are within the adaptive control 13aR. It should be understood that error sensor information from the plurality of error sensors 42a are provided to the adaptive control 13aR including N1R control filters 21aR and N2R control filters 21aR'. Although, band separated control is shown, it should be understood that both the N1R and N2R signal information could be passed directly into the control filter block as a

superimposed signal and convolved with a standard FIR, IIR filter, or the like.

In **Fig. 3c**, the outputs 87_{N1R} and 87_{N2R} from each control filter block **21aR** and **21aR'** are summed together to derive the raw digital output signal
5   to the AVA **40dR**. Likewise, output signals from other control filters (for example, indicative of higher order tones or contributions from left adaptive control) may also be summed at 88_{N1} and 88_{N2}. Optional power limiting **19aR** may be included to prevent overdriving of the AVA **40dR**. Power limiting is described in US Patent Application Serial Number 08/260,660 to Southward et
10   al. filed June 16, 1994 entitled "Active Control of Noise and Vibration." The combined output signals are then shaped by optional shaping filter **69aR** to normalize the control signals provided to the AVA **40dR**. The shaping filter is described in US Patent Application Serial Number 08/553,186 to Steenhagen, Southward, and Delfosse filed November 7, 1995 entitled
15   "Frequency Selective Active Adaptive Control System." The output signal is then transformed into analog form by the D/A converter **66aR**, filtered by analog output filter **64aR**, and finally amplified and conditioned by output amp and conditioner **65aR** to produce the dynamic drive signal to dynamically drive the AVA **40dR**.

20   With reference to **Fig. 3d**, the input, output, and control components associated with driving AVA **40dR'** located on right yoke **32bR** (**Fig. 3b**) are described. The components are similar to the previous embodiment, except for the input components. Tachometer signals from tachometer sensors **50R** and **50R'** are limited via limiters **55R, 55R'**. The signal is then locked onto
25   using PLLs **57R** and **57R'** which preferably include a divide step to multiply up the input signal frequency. The signal is then divided by divider **58R** and **58R'** to derive signals correlated with the **N1R** and **N2R** disturbance.

The reference signals indicative of **N1R** and **N2R** are then provided to adaptive control **13bR** which includes control filter blocks **21bR** and **21bR'**.

Elements within box **70bR** are preferably implemented in software. Error information is provided via the plurality of error sensors **42b**. It should be understood the error information from all error sensors may be provided to the adaptive control for the right yoke **32bR** in the fully-coupled case.

5   Likewise, output signals from other control filters may also be summed at 88_{N1} and 88_{N2}. However, it is preferable to decouple the right and left engines, such that the adaptive control **13bR** only receives reference signal information from the right engine and error information from the error sensors most strongly coupled to the AVA **40dR'**. This decoupling or

10 partitioning will be more fully described with reference to **Figs. 6a-6c**.

Fig. 3e illustrates the details of one preferred control architecture for the present invention ASC system **10a**. In particular, within the N1R control block **21aR** in the adaptive control **13aR** is an FIR control filter configuration including a preferable FIR control filter **11aR** which is preferably updated via

15 a preferably adaptive gradient descent update means. Preferably, Filtered-x Least Mean Square (LMS) method is used to update the weights of the N1R control filter **11aR**. The update means **71aR** preferably performs the weight update process based upon information derived via convolving the N1R signal with an error path model **72aR** and the error information from

20 plurality of error sensors. A description of this control architecture may be found in US Patent Application Serial Number 08/673,458 filed June 17, 1996 by Southward et al. entitled "Active Noise Or Vibration Control (ANVC) System And Method Including Enhanced Reference Signals."

The control block may include system identification **73aR** for deriving

25 the error path model **72aR**. The system ID can be performed in either an on-line or off-line fashion. The system ID involves obtaining the error path model, i.e., the transfer function between each error sensor-AVA pair. Preferably, the ID occurs by inducing low-level known and uncorrelated training noise **74aR** into the ASC system **10a** to derive the response thereto.

30 The error path model is then copied and used for all update means. A

further description of a preferable system identification method can be found in US Pat. Nos. 4,677,676 and 4,677,677 to Eriksson. Identical elements are included within the N2R control filter.

Fig. 3f describes a conventional FIR transversal filter, for example, the
5   transversal filter is the preferable form for the N1R control filter **21aR** shown in **Fig. 3e**. Transversal control filters, e.g. **21aR** have multiple taps 67_0, 67_1, 67_2, ..., 67_{n-1} which represent various values of x(k), in this example indicative of the **N1R** tone. The taps extract various x values, such as x(k), x(k-1), x(k-2) ..., x(k(n-1)) at successive unit increments from tapped delay line **68**. Each delay
10   block Z^{-1} represents a unit sample tap delay. Weights A_0, A_1, A_2, ..., A_{n-1} are individually adjusted in an adaptive fashion to accomplish the adaptation of the drive signal to each of the AVAs. The output signal y(k) from the transversal FIR filter is approximately governed by the following equation:

$$y(k) = x(k) A_0 + x(k-1) A_1 + x(k-2) A_2 + x(k-3) A_3 + ... + x(k-(n-1)) A_{n-1}$$

15   where:

y(k) =   output signal from control filter

n =   number of taps

A_0-A_{n-1} =   control filter weights

k =   unit step

20   As was indicated above, each weight A_0 through A_{n-1} is preferably updated by a filtered-x LMS method according to the equation:

$$A_0 (k+1) = A_0(k) + \mu \, e_k \, R(k)$$

where:

μ =   convergence coefficient

e_k =   error signal information

$R(k)$ =   filtered-x information

Updates to the weights A_0 through A_{n-1} can be accomplished in an on-line fashion and as fast as practicable.

5   Fig. 3g illustrates another possible control architecture which is useful in controlling an ASC system, such as the ASC system 10b and was described with reference to Fig. 3b. Alternatively, it could also be used with other embodiments described herein. Input signals indicative of N1R and N2R are provided to adaptive control 13bR, and to control filter blocks 21bR and 21bR'

10   included therein. The structure of the N1R block 21bR will be described. It should be understood that similar structures would be employed for the N2R block 21bR' and the control blocks for the left engine. The input signal N1R is provided to the control block 21bR and is separated into its in-phase and out-of-phase components, i.e., its quadrature components (sine and cosine-like

15   waves) in lines 75bR and 76bR, respectively. The out-of-phase component signal is provided by a 90 ° phase shift step in 90 ° phase shift block 77bR. The in-phase and out-of-phase components are provided to N1R and N1R' control filters 11bR and 11bR', to be convolved respectively therewith. The weights of the adaptive filters are preferably adjusted via an update method,

20   in particular, an adaptive gradient descent method, such as a Filtered-x LMS method, in adaptive update means 71bR and 71bR'. This type of control where the reference signals are split into quadrature components and separately convovled with control filters is hereinafter referred to as a "quadrature-type control."

25   The in-phase and out-of-phase component signals 75bR' and 76bR' are preferably also input to the C models 72bR and 72bR' (otherwise known as error path models) and convolved therewith to produce vector R, which is used in the adaptive weight update method along with the error signal information e(k) in lines 78bR and 78bR' from the plurality of error sensors

42bR.   The output from each control filter **11bR** and **11bR'** are summed together to produce the **N1R** drive signal to AVA **40dR'**.   The **N2R** drive signal in line **80bR'** is produced via similar means as is described for **N1R** control block **21bR** and is summed together at adder **79bR'** with the **N1R**

5   drive signal in line **80bR** to produce the combined drive signal to dynamically drive AVA **40dR'** at both frequencies thereby controlling noise and/or vibration within the cabin at both frequencies associated with **N1R** and **N2R**. It should be understood that other variations in control architecture are possible, such as Infinite Impulse Response (IIR) are also possible.

10   Fig. 3h   illustrates a frequency domain graphical plot of the actual performance comparison of a McDonnell Douglas DC-9-30 aircraft with JT8D engines including the baseline system (thin solid line) having yoke-attached passive TVAs (4 per engine) as compared to the novel ASC system **10b** (thick dotted line) of the present invention.   As is demonstrated, the sound pressure

15   levels at the **N1L, N2L** and **N1R, N2R** are reduced significantly.   In this case, even the tone at **2N1**, which is thought to be due to structural nonlinearities, is reduced.   The results were from a ground test with the left engine at 85% N1 power and the right engine at 90% N1 power.   The 90% N1 would be comparable to a high power cruise condition of the aircraft.   Separation of the

20   right and left engine frequencies during testing facilitated demonstration of reductions in tones produced by both right and left engines.   The data represents the results obtained at the location of a particular aft seat location at head height within the aft cabin and represents approximately a 25 dB reduction at the **N2L** tone and approximately 23 dB reduction at the **N1L** tone.

25   Average results were somewhat lower, but generally in the range of 15-20 dB. Notably, nowhere in the cabin was the sound pressure level perceptibly increased.   Further, even though there were only error sensors in the aft portion of the cabin, noise in the front portion of the cabin was also reduced.

    For comparison purposes and help in understanding the data, it should

30   be recognized that a halving of the sound pressure level occurs at 6 dB,

reduction by a factor of 4 occurs at 12 dB, reduction by a factor of 8 occurs at 18 dB, and reduction by a factor of 16 occurs at 24 dB. Therefore, it should be recognized that a reduction of 25 dB represents a 94% reduction in tonal sound pressure level and is very recognizable by the passenger.

5   Fig. 3i and Fig. 3j represent cross-sectional views of AVAs, for example a Single Degree Of Freedom (SDOF) AVA 40bR and an alternative Multiple Degree Of Freedom (MDOF) configuration 40bR" for attachment to yoke 32aR via brackets 62aR in the ASC system 10a. The details of the MDOF AVAs can be found in WO 96/12121 by Schmidt et al. entitled "Active Systems and

10   Devices Including Active Vibration Absorbers." In particular, the AVAs include one or more masses which can be preferably tuned to provide one or more resonant frequencies which substantially coincide with an operating condition and an active element therein for dynamically driving said one or more masses along, for example, a single defined axis A-A. It should be

15   understood that the AVAs are preferably uni-directional and produce active (real-time) vibrational forces along a defined axis and their produced vibration can be changed in both phase and magnitude.

Fig. 4a illustrates the preferred location of AVAs in the ASC system 10a on the yoke 32aR which attaches to the right engine 18aR as was described

20   with reference to Fig. 3a. Although, the right yoke 32aR is described in detail, it should be understood that the left yoke 32aL (Fig. 3a) would preferably be fitted with like ASC components. The yoke 32aR preferably attaches to the right engine 18aR via passive front mounts 56aR and 56aR' which include apertures 36a and 36a formed therein, respectively, for receiving attachment

25   members 29a and 29a', such as bolts or the like. Preferable passive aft mount which attaches the aft portion of engine to the aft pylon is not shown. Generally, the AVAs attach, at various locations, to the yoke 32aR which, in turn, attaches by way of yoke bolts 34aR and 34aR' to the outboard portion of the spar 38aR at the yoke's base portion 35aR. The yoke 32aR and spar 38aR

30   collectively comprise the pylon structure 28a. The pylon structure 28aR

attaches between the engine **18aR** and the fuselage **20a** and comprises the mechanical transmission path for vibration transmission to the fuselage **20a**.

Fuselage **20a** preferably includes stiffening means such as stringers **22a** and stiffening ring frames **24a**, for lateral and hoop-wise stiffening, and may
5   include an aft bulkhead **26a** with optional stiffening struts **30a** attached thereto. As illustrated, five (5) AVAs are shown in this side view of the ASC system **10a**. Two AVAs, **40eR** and **40dR** which are preferably Single Degree Of Freedom (SDOF) AVAs and are preferably attached adjacent to the terminal end portions **33a** and **33a'** of yoke **32a** by end brackets **61a** and **61a'**. Preferably,
10   the SDOF AVAs **40eR** and **40dR** at terminal end portions **33a** and **33a'** are tuned to have a resonant frequency **fn1** which substantially coincides with the most dominant **N2R** frequency (generally standard cruise frequency). By way of example, and not to be considered limiting, if the **N2R** cruise frequency were about 173 Hz, the AVAs **40eR** and **40dR** would be tuned such that their
15   resonant frequencies **fn1** would be just below the standard cruise frequency (tuned to about 170 Hz - approx. 98% of the most common operating frequency to be controlled).

Preferably, the terminally-positioned AVAs **40eR** and **40dR** are oriented to provide substantially radially-acting dynamic forces, as is indicated
20   by arrows labeled **RV** and **RV'**. It was discovered by the inventors that radial orientation and tuning to substantially coincide with **N2R** provides efficient and enhanced control of **N2R** vibrations of the right engine **18aR** which are transmitted into the yoke **32aR**. Optionally, the AVAs **40eR** and **40dR** may be MDOF AVAs which exhibit multiple resonant frequencies **fn1** and **fn2** which
25   may be tuned to substantially coincide with both the **N1R** and **N2R** frequencies. MDOF AVAs can be found in WO 96/12121 by Schmidt et al. entitled "Active Systems and Devices Including Active Vibration Absorbers."

Attached at the base portion **35aR** of yoke **32aR** are AVAs **40aR** and **40bR** which are preferably SDOF AVAs, which are preferably tuned such that

their resonant frequencies fn1 substantially coincide with the most common or predominant N1R frequency. Although, they will be driven at both N1R and N2R, tuning their passive resonances fn1 to substantially coincide with N1R will provide more efficient control of N1R vibrations. By way of example, and not to be considered limiting, there are preferably four AVAs attached at, or adjacent to, the base portion 35aR. Space permitting, they may be equally positioned at yoke bolts 34aR and 34aR'. Preferably, two AVAs are placed on each side of the yoke 32aR at the base portion 35aR, one at each bolt location. Preferably, the AVAs act in a direction selected from the group consisting of the radial, tangential, or fore and aft directions (Fig. 5a).

AVA 40bR is shown acting substantially in the radial direction (directed toward the center of engine 18aR) as indicated by arrow RV" (radial vector) and is attached to the yoke 32aR via base bracket 62aR and yoke bolt 34aR. AVA 40aR is shown acting tangentially as is indicated by arrow TV (tangential vector, i.e., tangential to the radial vector) and may also be attached to yoke 32aR via bracket 62aR and yoke bolt 34aR. The other AVAs and their locations are described with reference to Fig. 5a. Optional AVA 40cR is shown oriented in a part radial-part tangential orientation as indicated by arrow RTV (radial-tangential vector) and is attached by bracket 62aR' and yoke bolt 62aR'. Additionally, AVAs located at the base portion 35aR may also be MDOF AVAs. Combinations of MDOF and SDOF AVAs may be desirable, as, in general, where space is available, a MDOF AVA will provide enhanced control of both N1R and N2R vibrations.

Fig. 4b illustrates an forward-looking view of a portion of another embodiment of the ASC system 10c. In this embodiment, accelerometers located on the pylon structure 28cR are used as the error sensors in place of microphones located in the aircraft cabin. These accelerometers provide the residual error signals (indicative of vibration) for use in controlling the AVAs. Preferably, accelerometers 63ytr and 63ytr' are located at or near the terminal ends 33cR and 33cR' of yoke 32cR and are substantially collocated

with the radially-acting AVAs 40dR and 40eR and provide radial acceleration information indicative of the residual vibration thereat. Likewise, accelerometers 63ybt and 63ybr provide measurements of the residual vibration of the base portion 38cR of the yoke 32cR in the tangential and
5   radial directions, respectively. Preferably, accelerometers 63ybt and 63ybr are substantially collocated with tangentially-acting AVA 40aR and radially-acting AVA 40bR. Alternatively, or additionally, accelerometers, such as 63sv and 63sl may be placed on the spar 38cR to provide measurements of residual vibration in the vertical and lateral directions, respectively. Notably,
10   placement of error sensors on the spar 38cR would require more elaborate error models as compared to collocation of the error sensors with the AVAs. Likewise, multiple accelerometers placed on the fuselage 20c, such as 63fv, may also be used to control the vibration of the fuselage 20c caused vibration of engine 18cR. Controlling the dominant modes of vibration that are
15   coupled with the acoustic volume within the aircraft cabin is thought to control the acoustic noise produced therein.

Fig. 5a illustrates an forward-looking view of the ASC system 10a, less engines, illustrating the right and left yokes 32aL and 32aR (each of which is turned 90° aft for clarity, i.e., the fore and aft directions for each yoke are
20   shown with arrows) with interconnection to the fuselage 20a indicated by heavy-dotted lines HD and HD'. The right hand yoke 32aR, and the locations of AVAs thereon, will be described in detail. It should be understood that the AVA numbers, attachments, locations, and directions of action on left hand yoke 32aL, as indicated by AVAs 40aL, 40bL, 40dL, 40eL, 40fL, and 40gL are
25   preferably identical to that of the right hand yoke 32aR.

Shown on the right hand yoke 32aR is the first preferred configuration of AVAs. At the terminal end portions 33a and 33a' are located AVAs 40dR and 40eR which are preferably SDOF AVAs which act in a substantially radial direction and are preferably tuned to exhibit a resonant frequency
30   substantially coinciding with the N2R rotational frequency of right engine

18aR (e.g. Fig. 4a). AVAs **40aR, 40bR, 40gR** and **40fR** attach at the base portion **35aR** on opposite sides of yoke **32aR** adjacent to the point of attachment of yoke **32aR** to spar **38aR**. Preferably, the base-portion-mounted AVAs are also SDOF AVAs and are preferably tuned such that each exhibits a natural

5   frequency which substantially coincides with the N1R operating frequency.

Alternatively, where the space and weight considerations allow, Multiple Degree Of Freedom (MDOF) AVAs may be used and attached to the yoke **32aR**. Optional AVA locations/directions are illustrated for optional AVAs **40hR** and **40cR** wherein the AVAs are directed to act substantially in a

10   fore and aft direction (AVA **40hR**) or in a direction having components of both the radial and tangential (AVA **40cR**). In particular, it was discovered by the inventors that tuning the preferably at least four AVAs, **40aR, 40bR, 40gR** and **40fR** to have resonant frequencies that substantially coincide with N1R frequency is particularly effective at controlling N1R vibrations, which if

15   transmitted to the spar **38aR**, would be responsible for annoying N1R tones emerging in the aircraft cabin **44a**. Although, the AVAs may be tuned to one particular frequency, it is desirable to actuate them at multiple frequencies (both N1R and N2R). For example, AVAs **40aR** and **40gR** are directed to act in substantially tangential directions and are preferably each tuned to exhibit

20   natural frequencies substantially coincident with N1R, however, the AVAs **40aR** and **40gR** would also be driven at the N2R frequency, albeit they would be less effective at that frequency as if the AVA were tuned to have a natural frequency substantially coincident at N2R.

Furthermore, where MDOF AVAs can be used, they are preferably

25   tuned to exhibit first and second resonant frequencies which substantially coincide with both N1R and N2R, and thereby both frequencies may be actuated to control vibration with improved efficiency. Likewise, AVAs **40bR** and **40fR** are directed to act in substantially radial directions and are preferably each tuned to exhibit natural frequencies substantially coincident with N1R.

30   Alternatively, one of the tangential AVAs, such as **40gR** may be replaced with

fore-and-aft acting AVA, such as **40hR** or a radial acting AVA, such as **40bR**. For clarity, the Amp, filter and D/A or A/D converters as described with reference to **Fig. 3a** are collectively labeled **cond.** (short for conditioning).

5   **Fig. 5b**, **Fig. 5c** and **Fig. 5d** illustrate side views of the right yoke assemblies used on various alternative ASC systems similar to the ASC system **10a**, except each illustrates on right yokes **32eR**, **32fR**, and **32gR** different embodiments of preferred locations and directions of AVAs. On the yoke **32eR** (shown in **Fig. 5b**) one preferred embodiment including AVAs **40aR**, **40bR**, **40dR₁**, **40dR₂**, **40eR₁**, **40eR₂**, **40fR**, **40hR**, and **40gR** is illustrated.
10   The main difference between the **Fig. 5a** configuration and the **Fig. 5b** configuration is that two AVAs, such as **40dR₁**, **40dR₂**, and **40eR₁**, **40eR₂**, are located at each of the terminal ends **33eR** and **33eR'** of the yoke **32eR**. These are preferably SDOF AVAs, preferably act in a substantially radial direction, and are preferably tuned to exhibit natural frequencies substantially
15   coincident with **N2R**. Illustrated on the right yoke **32fR** is another embodiment including another configuration of AVAs **40aR**, **40bR**, **40eR**, **40fR**, **40gR**, and **40jR**. Illustrated on the right yoke **32gR** is another embodiment including another configuration of AVAs **40aR**, **40bR**, **40eR**, **40fR**, **40gR**, and **40hR**. It was discovered experimentally by the inventors that
20   the **Fig. 5b** configurations of AVAs yields particularly effective cancellation of noise within the cabin. Furthermore, it is anticipated that the preferred configurations of **Fig. 5c** and **5d** will provide substantially equivalent vibration control results as compared to the **Fig. 5b** configuration with less AVAs required.

25   **Fig. 6a** illustrates a block diagram of the ASC system **10a** and illustrates the partitioning/decoupling between the right and left side AVA control. The system **10a** includes left engine reference signal generating means **82aL**, right engine reference signal generating means **82aR**, each for providing the signals indicative of **N1L**, **N2L** and **N1R**, **N2R** to the controller **46a**. Within
30   controller **46a** are left adaptive control **13aL** and right adaptive control **13aR**

for providing adapted output signals to the right AVA bank **84aR** (including m number of right AVAs (**RAVA₁** through **RAVAₘ**)) and left AVA bank **84aL** (including **m** number of left AVAs (**LAVA₁** through **LAVAₘ**)). Included within left and right adaptive control **13aL** and **13aR** are N1R, N2R and N1L,

5   N2L control blocks **21aR** and **21aR'** and **21aL** and **21aL'** which include the adaptive filters. Error sensor information from error signal generating means **86a** including L number of microphones within the cabin are provided to both the right and left adaptive control **13aL** and **13aR**. It should be understood that in the reference sensor partitioned case, left engine reference

10   signal generating means **82aL** is provided only to be used in the left adaptive control **13aL** for driving the left AVA bank **84aL** and right engine reference signal generating means **82aR** is provided only to be used in the right adaptive control **13aR** for driving the right AVA bank **84aR**. Notably, error sensor information from error signal generating means **86a** is used in all

15   control blocks in this embodiment.

Fig. **6b** illustrates a block diagram of the ASC system **10b**. It is substantially similar to the system described with reference to Fig. **6a**, except that the reference signal generating means **82bL** and **82bR** comprise tachometer sensors.

20   Fig. **6c** illustrates a block diagram of the ASC system **10c** previously described with reference to Fig. **4b**. In this embodiment, the ASC system **10c** is further decoupled in that the right adaptive control **13cR** only receives error information from the right error bank **86cR** (including **n** number of accelerometers **accel L1** through **accel Ln**) and the left adaptive control **13cL**

25   only receives error information from the left error bank **86cL** (including **n** number of right accelerometers **accel R1** through **accel Rn**). Likewise, the left engine reference signal generating means **82cL** is provided only to be used in the left adaptive control **13cL** for driving the left AVA bank **84cL** (including **m** number of left AVAs **LAVA₁** through **LAVAₘ**) and right engine reference

30   signal generating means **82cR** is provided only to be used in the right

adaptive control **13cR** for driving the right AVA bank **84aR** (including m number of right AVAs **RAVA₁** through **RAVA_m**). Generally, it is preferable that number of left accelerometers exceed the number of left AVAs **(n>m)** and number of right accelerometers exceed the number of right AVAs **(n>m)**.

5   **Fig. 7a** illustrates an ANVC system **10k**, and in particular, is intended to aid in describing alternative reference signal processing that may be employed, which has potentially broader applicability than the ASC systems previously described with reference to the previous **Fig. 3a** through **Fig. 6c**. In particular, this aspect of the invention relates to a novel means and method

10   for providing an input signal to an adaptive control **13k**. In more detail, the ANVC system **10k** (including the subset ASC system, example **10a** (Fig. 3a) embodying the invention comprises at least one reference sensor **50k**, which can be either a tachometer sensor or an accelerometer for providing a signal indicative of a disturbance source **18k**, such as an aircraft engine, automobile

15   engine, or the like. The raw signal indicative of, for example, **N1R** of the vehicle engine (generally a sinusoid-like wave) is conditioned within input conditioning block **89k** to provide a conditioned reference signal. Within input conditioning block is a limiter **55k** which conditions the signal as is shown with reference to **Fig. 7b**, a PLL **57k**, and a Divider **58k**.

20   First, the sinusoid wave **90k** indicative of **N1R** is transformed into a square wave via a hysteresis process step. The square wave **91k** indicative of the **N1R** frequency is generated by triggering on predetermined positive (+) voltage and negative (-) voltage values of the sinusoid wave **90k**. The peak values of the square wave **91k** correspond to the peak values of the sinusoid

25   wave **90k**. Next, as shown in **Fig. 7c**, the magnitude of the square wave signal **91k** is clipped within limiter **55k** to predetermined voltage values (+V, -V) to form the clipped signal **92k** indicative of the **N1R** frequency. This clipped signal **92k** is then inputted into a PLL **57k**. The PLL **57k** locks onto the predominant **N1R** frequency component. A divider **93k** in the comparator

30   leg **94k** divides by an integer multiple, with the resultant effect of multiplying

up the frequency of the clipped signal 92k by that integer multiple. If a tachometer sensor is used for the reference sensor 50k, the integer multiple may comprise a gear ratio portion, as before described, and also some preferably power-of-two factor (e.g. 8, 16, 32, 64, 128, 256, ...) for further
5   multiplying up the signal frequency. Optional divide 58k is needed only if the raw tachometer signal indicative of N1R needs to be further geared up or down. If a reference accelerometer is used, the signal will already be at the N1R frequency and divider 58k would be unneeded. Additional conditioning, such as using ALEs, may be required before entering the
10   conditioning block 89k if the raw N1R signal has unacceptable superimposed noise thereon.

The conditioned and multiplied reference signal 95k exiting the conditioning block 89k is provided to digital input generator 99k which includes a counter, such as a modulo counter 96k. The modulo counter 96k
15   continuously generates a count from a minimum value to a maximum value. For example, the count may be from 0 to a power-of-two number minus one (example, $2^R-1 = 7, 15, 31, 63, 127, 255$, where R = the number of bits), as shown in **Fig. 7d.** The count is based upon the conditioned reference signal. In other words, for each cycle, example cycle 1, cycle 2, ..., the signal is
20   divided into a power-of-two number of increments (counts). When the counter gets to the end, it simply starts over at zero. A storage means, such as a lookup table 97k, has sinusoidal input values stored therein representative of each count. The individual input values stored in the table for each count, as shown in **Fig. 7e,** are determined according to the equation:

25   Value = Sin [count x (2 π/total count)]

For example, if the frequency multiplier were 256, then there would be 256 counts per cycle and 256 values (0 through 255) stored in the table. Means for extracting the individual ones of the stored input values, such as a digital Input/Output (IO) **98k** which reads the count from modulo counter **96k** and

provides the count to software which then extracts the appropriate corresponding input value from the lookup table **97k**. The stream of input values extracted from the table **97k** which is based upon the count from modulo counter **96k** collectively comprise an input signal indicative of **N1R**

5   which can be fed directly to the adaptive control filter **11k** (example an FIR filter) in adaptive control process **13k**.

The signal optionally may be fed to an error path model **72k** to be used by the adaptive update means **71k** along with the error sensor information from at least one error sensor, for example, a microphone **42k**, or an

10   accelerometer **63k** to update the weights of the control filter **11k**. The update method is preferably Filtered-x LMS, or the like. The output of the control **13k** is used to drive at least one output transducer, for example, an active mount **12k**, a loudspeaker **16k**, or an AVA **40k** to produce active noise and/or vibration and control noise and/or vibration within control volume **44k**. It

15   should be understood that the use of the modulo counter is optional and that an signal indicative of N1 could be used directly by the adaptive control. It should also be understood that multiple modulo counters could be used to provide multiplied signals indicative of **N1R, N2R, N1L, N2L** for vehicles such as aircraft. Further, if a quadrature-type control is utilized, it should be

20   understood that a second signal could be derived which lags by 90° from the first signal by implementing a delay of 1/4 wavelength (1/4 the total number of counts). Therefore, a sine and a cosine wave for input to the adaptive control could be generated from the table. Similarly, a separate table could include the phase shifted (cosine) values.

25   While several embodiments, including the preferred embodiment of the present invention, have been described in detail, various modifications, alterations, changes and adaptations to the aforementioned may be made without departing from the spirit and scope of the present invention defined in the appended claims. It is intended that all such modifications, alterations

30   and changes be considered part of the present invention.

What is claimed is:

1.   An Active Structural Control (ASC) system (10) for controlling acoustic noise and/or vibration generated within an aircraft cabin (44) that results from vibration generated by at least one engine (18), said vibration

5   which is transmitted into a pylon structure (28) which attaches between said at least one engine (18), and an aircraft fuselage (20), said pylon structure (28) preferably including a yoke (32) and a spar (38), and causes vibration of said aircraft fuselage (20), thereby generating said acoustic noise and/or vibration within said aircraft cabin (44), said ASC system system (10), comprising:

10   (a)   a plurality of error sensors (42, 63) for providing a plurality of error signals,

(b)   at least one reference sensor (49, 50) associated with said at least one engine (18), for providing at least one reference signal indicative of an engine rotation,

15   (c)   a plurality of Active Vibration Absorbers (AVAs) (40) directly attached to said yoke (32), and

(d)   a controller (46) for processing said group consisting of said first reference signal and said second reference signal and said plurality of error signals and providing a plurality of output signals to said plurality of AVAs

20   (40) to effectuate vibration of said yoke (32) and resultantly control acoustic noise and vibration within said aircraft cabin (44).

2.   An ASC system (10) of claim 1 wherein said at least one reference sensor (50) is at least one selected from a group consisting of:

(i) a first reference signal indicative of an N1 engine rotation, and

25   (ii) a second reference signal indicative of an N2 engine rotation.

3. An ASC system (10) of claim 1 wherein said at least one reference sensor comprises at least two reference sensors, a first reference sensor (50) to provide said first reference signal indicative of an N1 engine rotation of said at least one engine (18) and a second reference sensor (50') to

5 provide said second reference signal indicative of an N2 engine rotation of said at least one engine (18).

4. An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of a plurality of Single Degree Of Freedom (SDOF) AVAs wherein a natural frequency (fn1) of said SDOF AVAs is tuned to

10 substantially coincide with an engine rotation frequency selected from a group consisting of an N1 engine rotation frequency and an N2 engine rotation frequency.

5. An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of at least one Single Degree Of Freedom (SDOF)

15 AVA located at a terminal end portion of said yoke (32) which is tuned to exhibit a natural frequency which substantially coincides with an N2 engine rotation frequency and at least one Single Degree Of Freedom (SDOF) AVA located on said yoke (32) at a base portion thereof where said yoke (32) connects to said spar (38) wherein said at least one SDOF AVA located on said

20 yoke (32) at said base portion is tuned to exhibit a natural frequency which substantially coincides with an N1 engine rotation frequency.

6. An ASC system (10) of claim 1 wherein separate tachometer sensors (50, 50') provide said first and said second reference signals indicative of said N1 engine rotation and said N2 engine rotation, respectively.

25 7. An ASC system (10) of claim 6 wherein said first and said second reference signals indicative of said N1 engine rotation and said N2 engine rotation are converted into exact N1 and N2 frequency signals by a gear ratio.

8.   An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are substantially directed to produce active forces in at least two directions selected from the group consisting of radial, tangential, and fore and aft directions.

9.   An ASC system (10) of claim 8 wherein said plurality of AVAs (40) are further comprised of AVAs selected from group consisting of Single Degree Of Freedom (SDOF) AVAs and Multiple Degree Of Freedom (MDOF) AVAs.

10.   An ASC system (10) of claim 8 further including at least one Single Degree Of Freedom (SDOF) AVA directed to act substantially in one direction selected from a group consisting of a radial direction, a tangential direction, and a fore and aft direction wherein said at least one SDOF AVA is located on said yoke (32) at a base portion thereof where said yoke (32) connects to said spar (38).

11.   An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of at least one Single Degree Of Freedom (SDOF) AVA acting only in a substantially radial direction and located at a terminal end portion of said yoke (32).

12.   An ASC system (10) of claim 1 wherein said controller (46) is decoupled to have a first multiple of control filters (13L) and a second multiple of control filters (13R), wherein said first multiple (13L) is used to control a first bank of plurality of AVAs (84L) associated with a first aircraft engine (18L), and said second multiple is used to control a second bank of plurality of AVAs (84R) associated with a second aircraft engine (18R).

13.   An ASC system (10) of claim 12 wherein said first multiple of control filters (13L) only receives reference signal information from said first aircraft engine (18L) and said second multiple of control filters (13R) only receives reference signal information from said second aircraft engine (18R).

14.   An ASC system **(10)** of claim 12 wherein said first multiple of control filters **(13L)** only receives error signal information from a first bank of accelerometers **(86L)** associated with said first aircraft engine **(18L)** and said second multiple of control filters **(13R)** only receives error signal information from a second bank of accelerometers **(86R)** associated with said second aircraft engine **(18R)**.

15.   An ASC system **(10)** of claim 12 wherein each of said first and said second multiple of control filters **(13L, 13R)** are used to control a plurality of Single Degree Of Freedom (SDOF) AVAs in each of said first and said second banks **(84L, 84R)** wherein at least one of said plurality of SDOF AVAs within each said bank **(84L, 84R)** acts in a substantially radial direction and at least one of said plurality of SDOF AVAs within each said bank **(84L, 84R)** acts in a substantially tangential direction.

16.   An ASC system **(10)** of claim 1 wherein said plurality of error sensors **(42, 63)** are microphones which are only located in an aft half portion of said aircraft cabin **(44)**.

17.   An ASC system **(10)** of claim 1 wherein said plurality of error sensors **(42, 63)** are accelerometers **(63)** which are located on at least one selected from a group consisting of said spar **(38)**, said yoke **(32)**, and said aircraft fuselage **(42)**.

18.   An ASC system **(10)** of claim 17 wherein at least one of said accelerometers **(63)** is substantially collocated with at least one of said plurality of AVAs **(40)**.

19.   An ASC system **(10)** of claim 1 wherein said at least one reference sensor **(49, 50)** is further comprised of at least one selected from a group of sensors consisting of:

i) an accelerometer sensor **(49)** located on said at least one engine **(18)**, and

ii) at least one tachometer sensor (50).

20.   An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of:

a) at least one Single Degree Of Freedom (SDOF) AVA, and

b) at least one Multiple Degree Of Freedom (MDOF) AVA.

21.   An ASC system (10) of claim 1 wherein said plurality of active vibration absorbers (40) are further comprised of:

a) a Single Degree Of Freedom (SDOF) AVA located at at least one of a first and a second terminal end portion of said yoke (32) and which is tuned to exhibit a resonant frequency which substantially coincides with an N2 engine rotation frequency and which acts in a substantially radial direction, and

b) at least four Single Degree Of Freedom (SDOF) AVAs located on said yoke (32) at a base portion thereof where said yoke (32) connects to said spar (38) and wherein at least one of said at least four SDOF AVAs is tuned such that it exhibits a natural frequency which substantially coincides with an N1 engine rotation frequency.

22.   An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of an AVA set including orthogonally arranged AVAs.

23.   An ASC system (10) of claim 1 wherein said at least one engine (18) further comprises a right engine (18R) and a left engine (18L) and a plurality of AVAs (40) attached to each of a right yoke (32R) and a left yoke (32L) wherein at least one AVA is located at a first terminal end portion of said right and left yokes (32R, 32L) and at least one AVA is located at a base portion of said left and right yoke (32R, 32L).

24.   An ASC system (10) of claim 1 further including means for further processing said at least one reference signal (49, 50), comprising the steps of:

5   i)   conditioning said signal indicative for producing a conditioned reference signal (95k),

ii)   counting by a modulo counter (96k) for continuously generating a count from a minimum value to a maximum value based upon said conditioned reference signal (95k),

iii)   storing a plurality of individual input signal
10   values, and

iv)   extracting individual ones of said plurality of individual input signal values based upon said count to derive an input signal for input to said adaptive control (13k).

25.   An ASC system (10) of claim 24 wherein said modulo counter
15   (94k) includes a power-of-two count including 2^R-1 counts, where R is a number of registers.

26.   An ASC system (10) of claim 24 wherein said modulo counter (94k) increments from a minimum value of 0 to a maximum value of 255.

27.   An ASC system (10) of claim 24 wherein said means for storing
20   is a lookup table (97k).

28.   An ASC system (10) of claim 27 wherein said lookup table (97k) has 256 stored values corresponding to 256 counts.

29.   An ASC system (10) of claim 24 wherein said signal provided to said modulo counter (94k) is a power-of-two factor (e.g. 8, 16, 32, 64, 128, 256)
25   higher in frequency than an engine rotation frequency selected from the group consisting of:

i) an N1 engine rotation frequency of an aircraft engine (18), and

ii) an N2 engine rotation frequency of an aircraft engine (18).

30. An ASC system (10) of claim 24 wherein said means for extracting individual ones of said plurality of input signal values is a Digital IO device (98k).

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Fig. 1
Prior Art

Fig. 2
Prior Art

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Fig. 3a

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Fig. 3b

Fig. 3c

Fig. 3d

Fig. 3e

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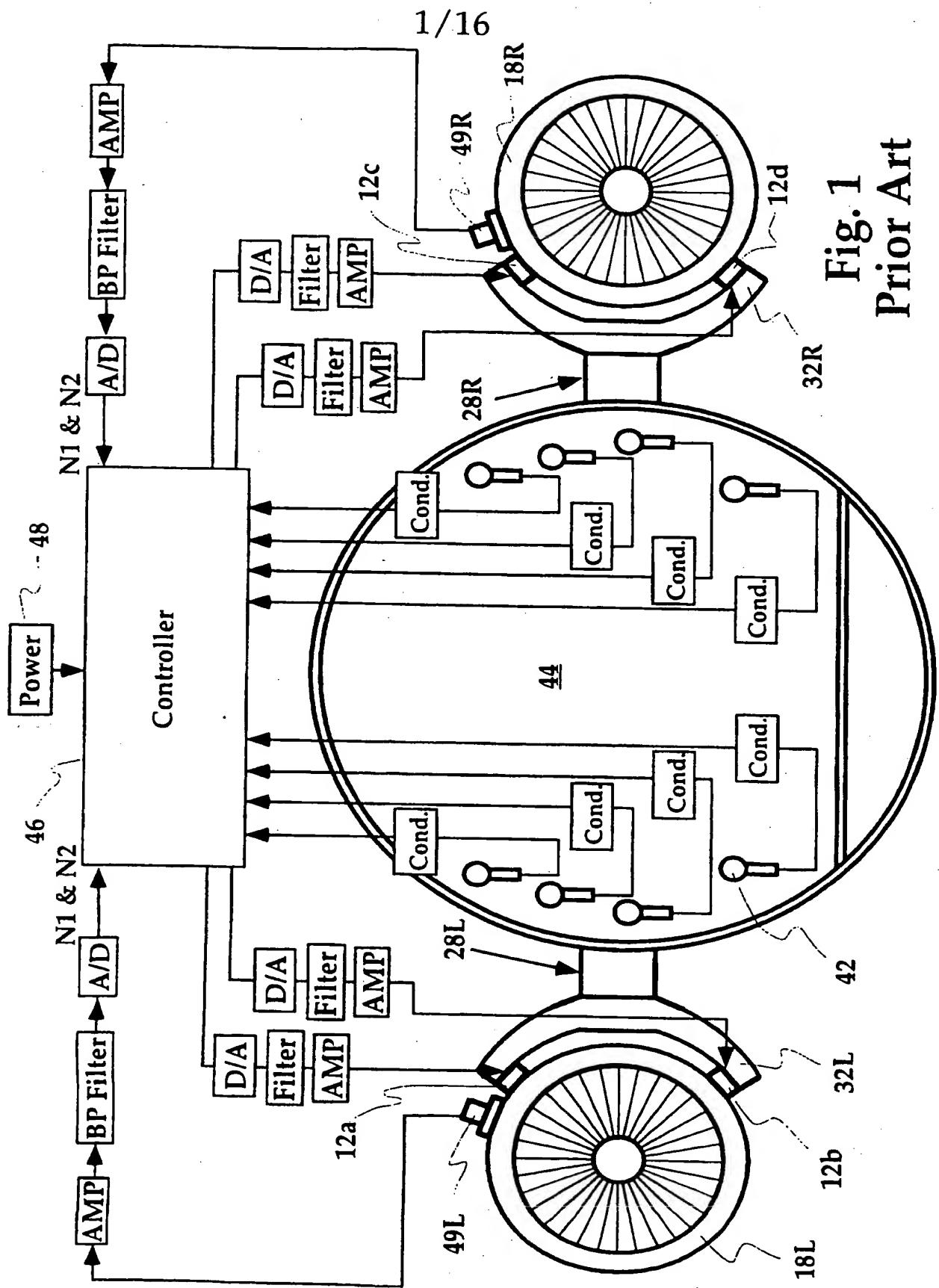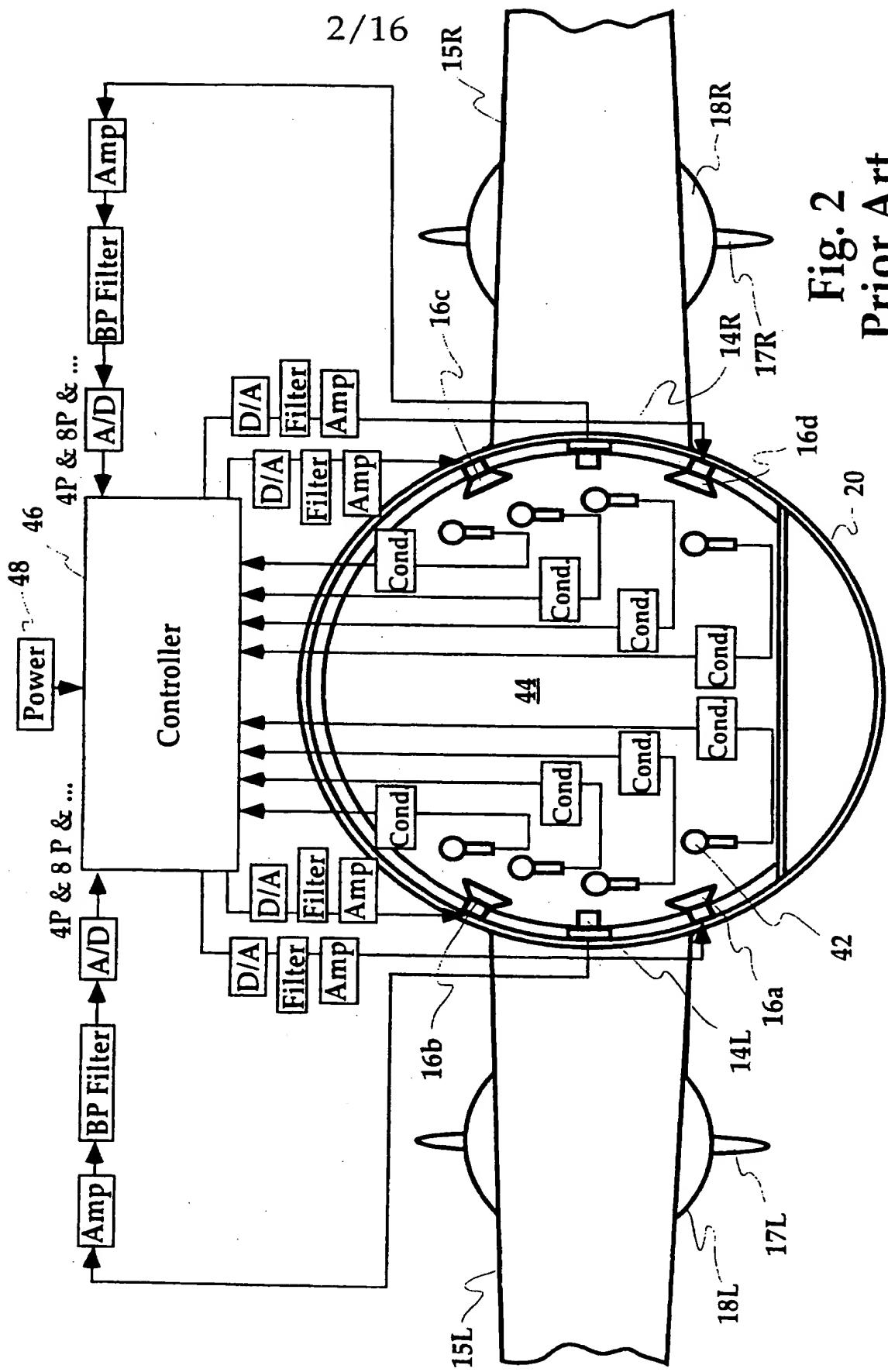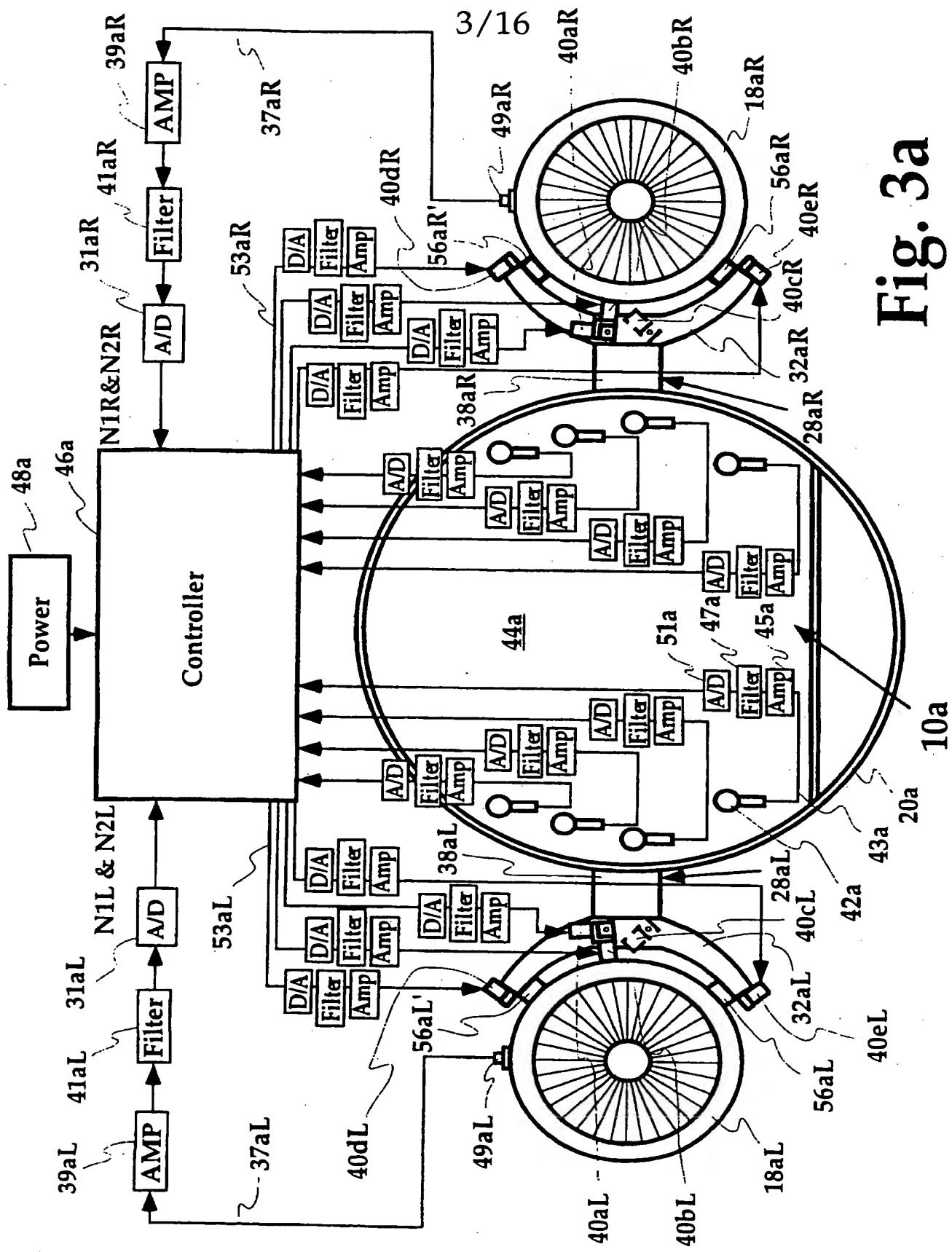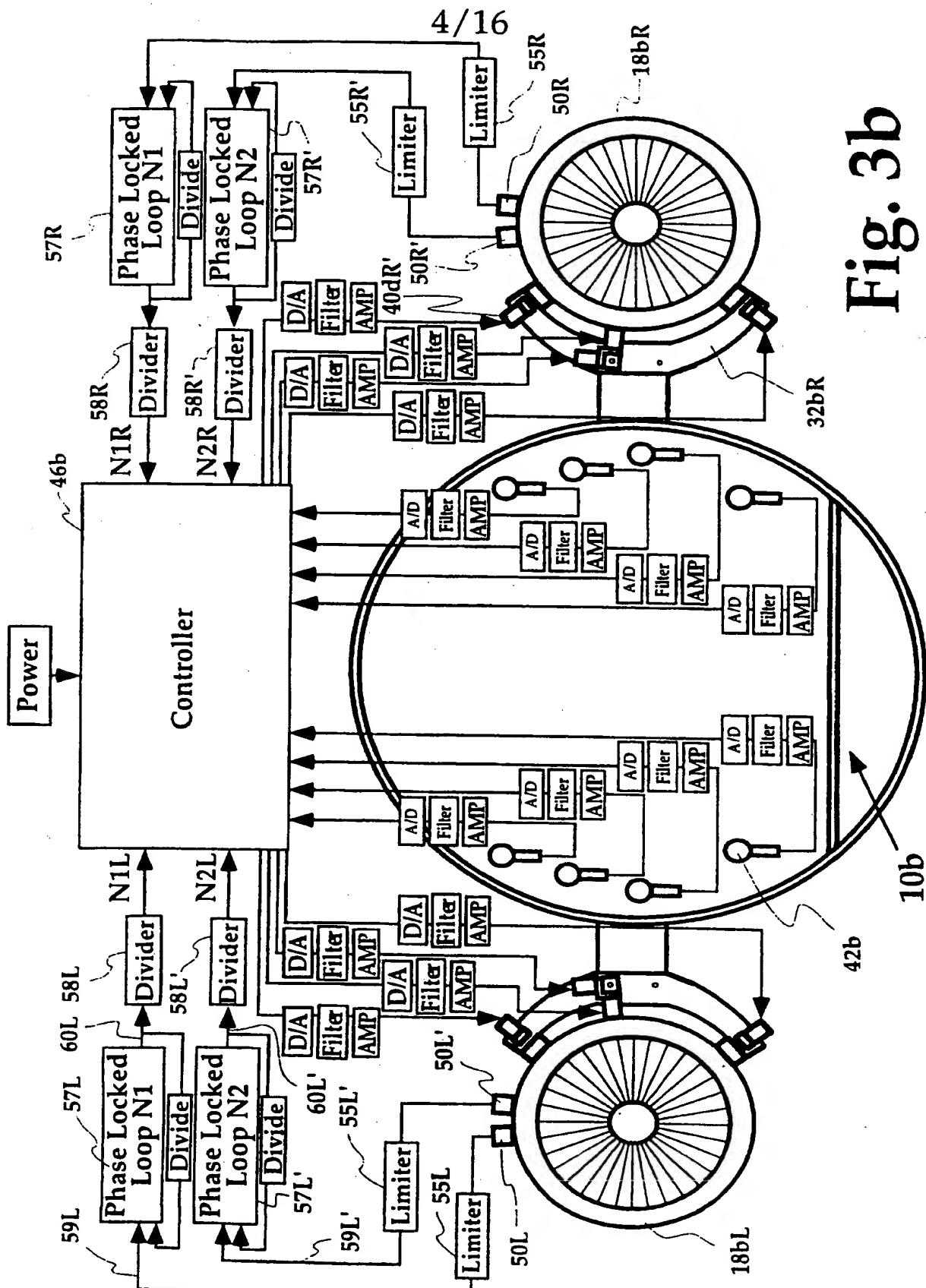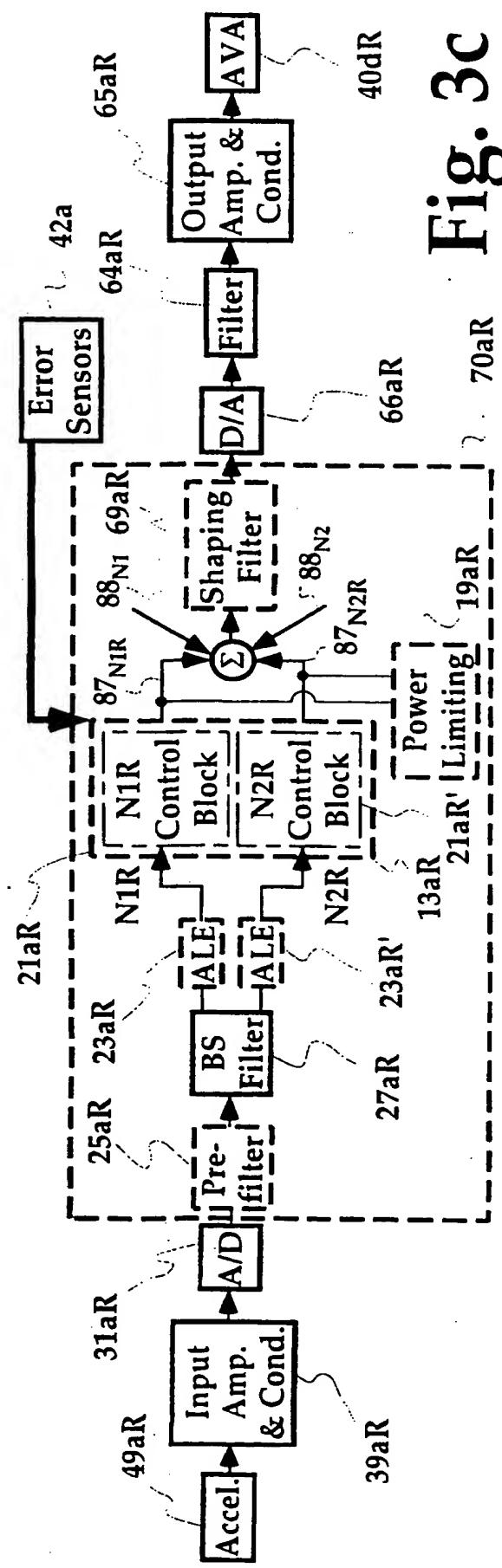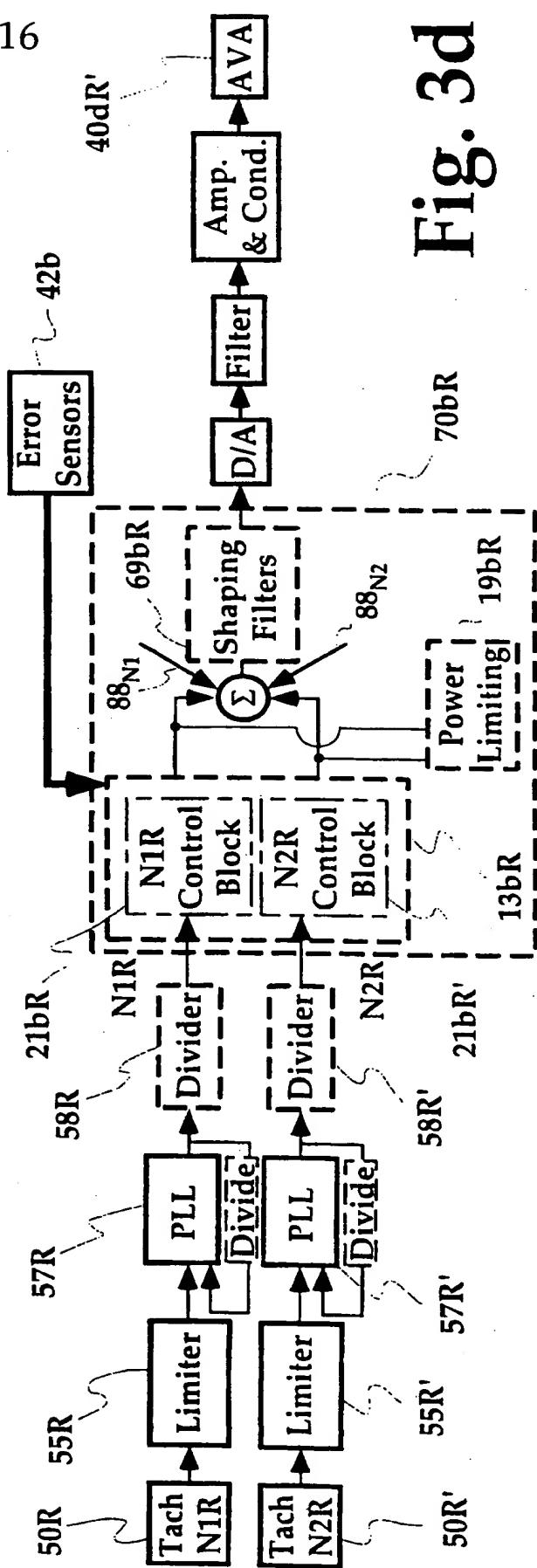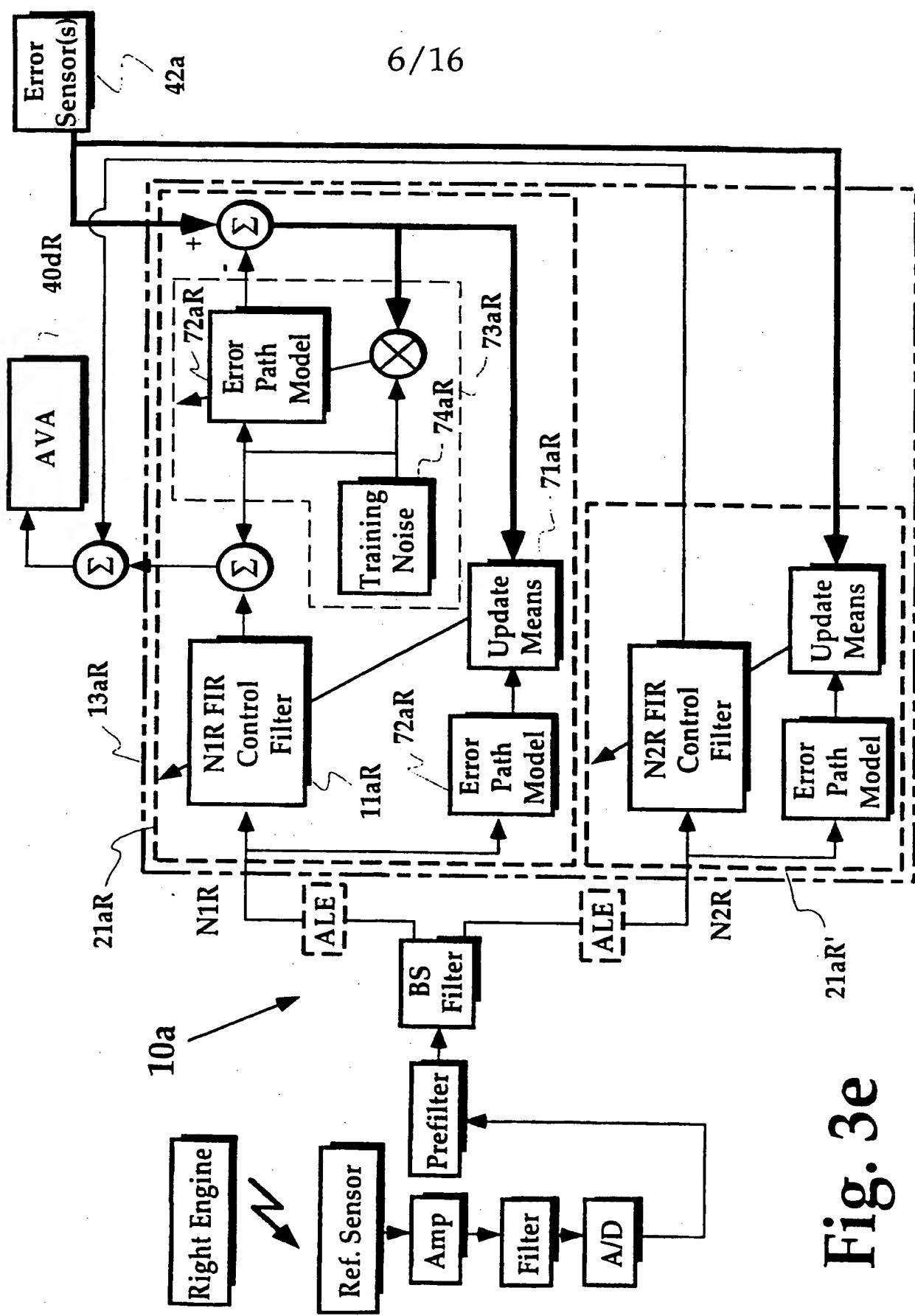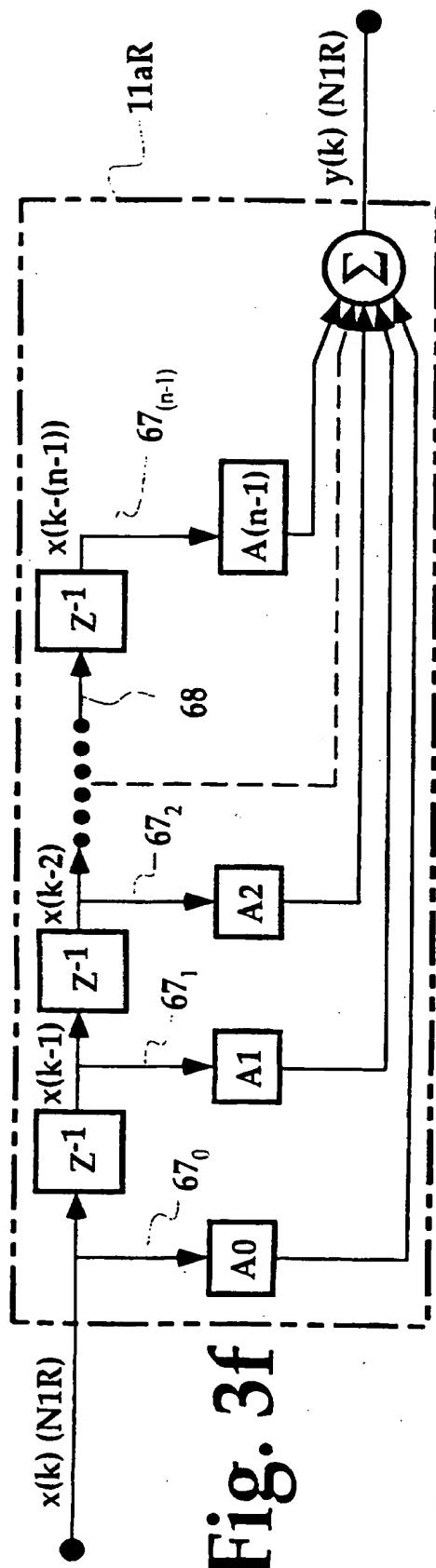
Fig. 3f
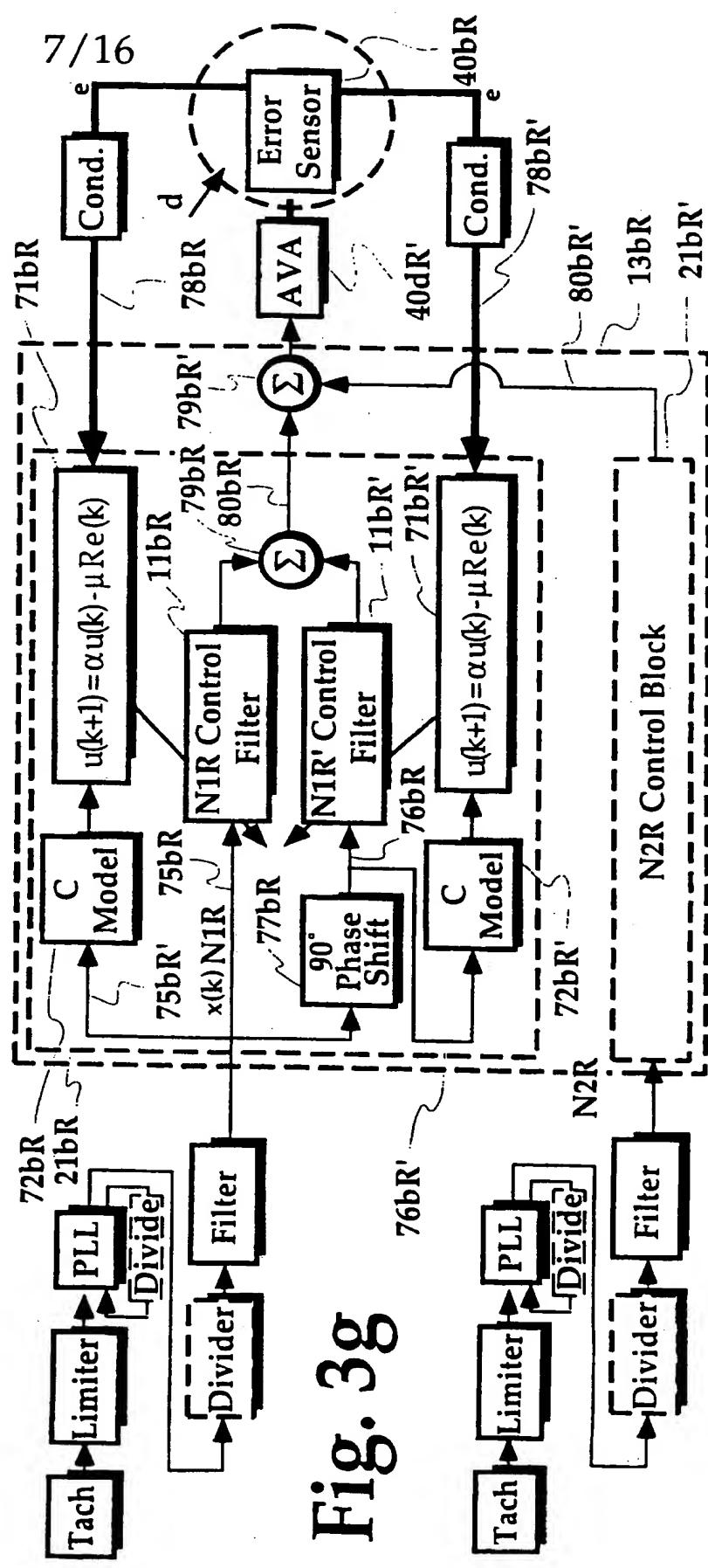
Fig. 3g

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Fig. 3h

Fig. 3i

Fig. 3j
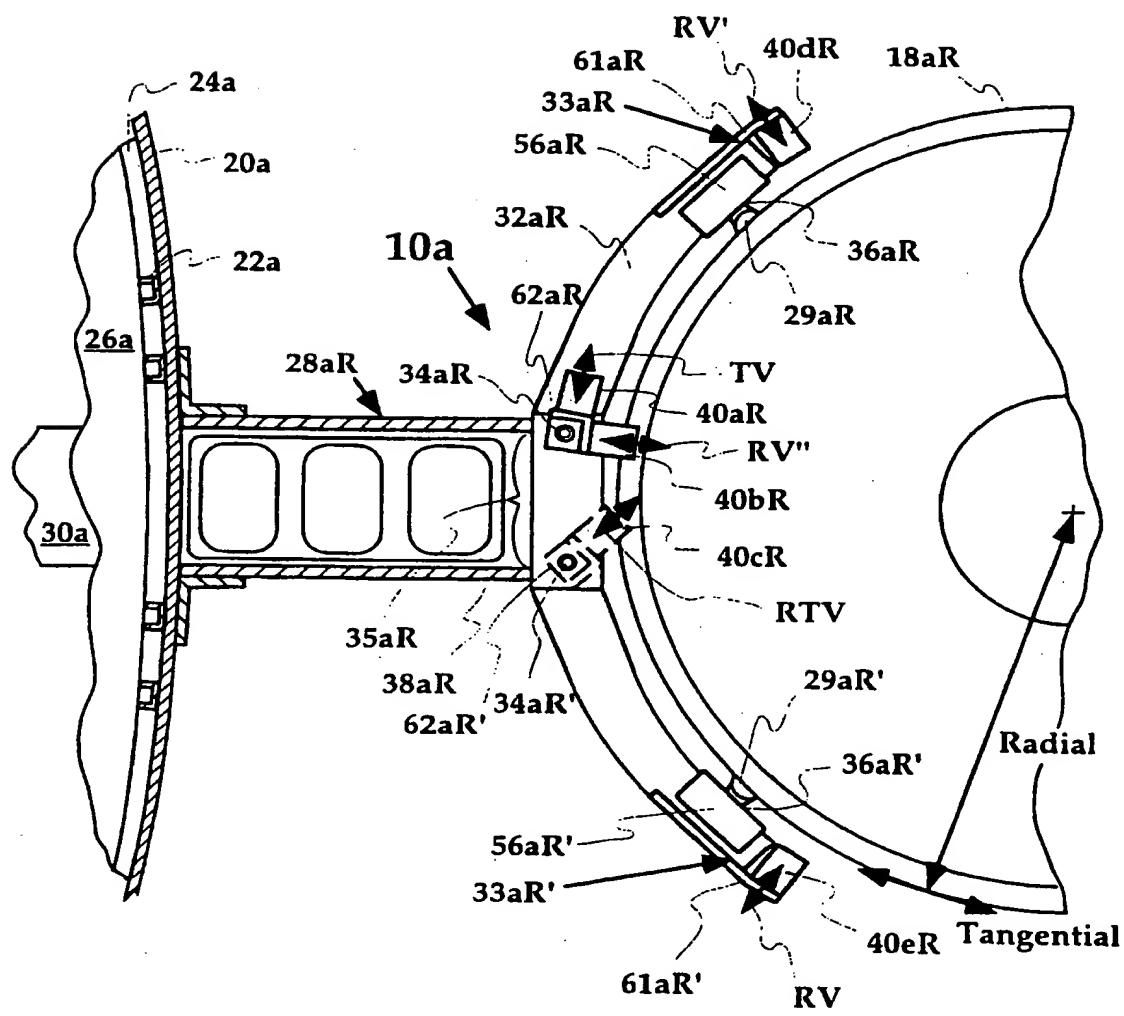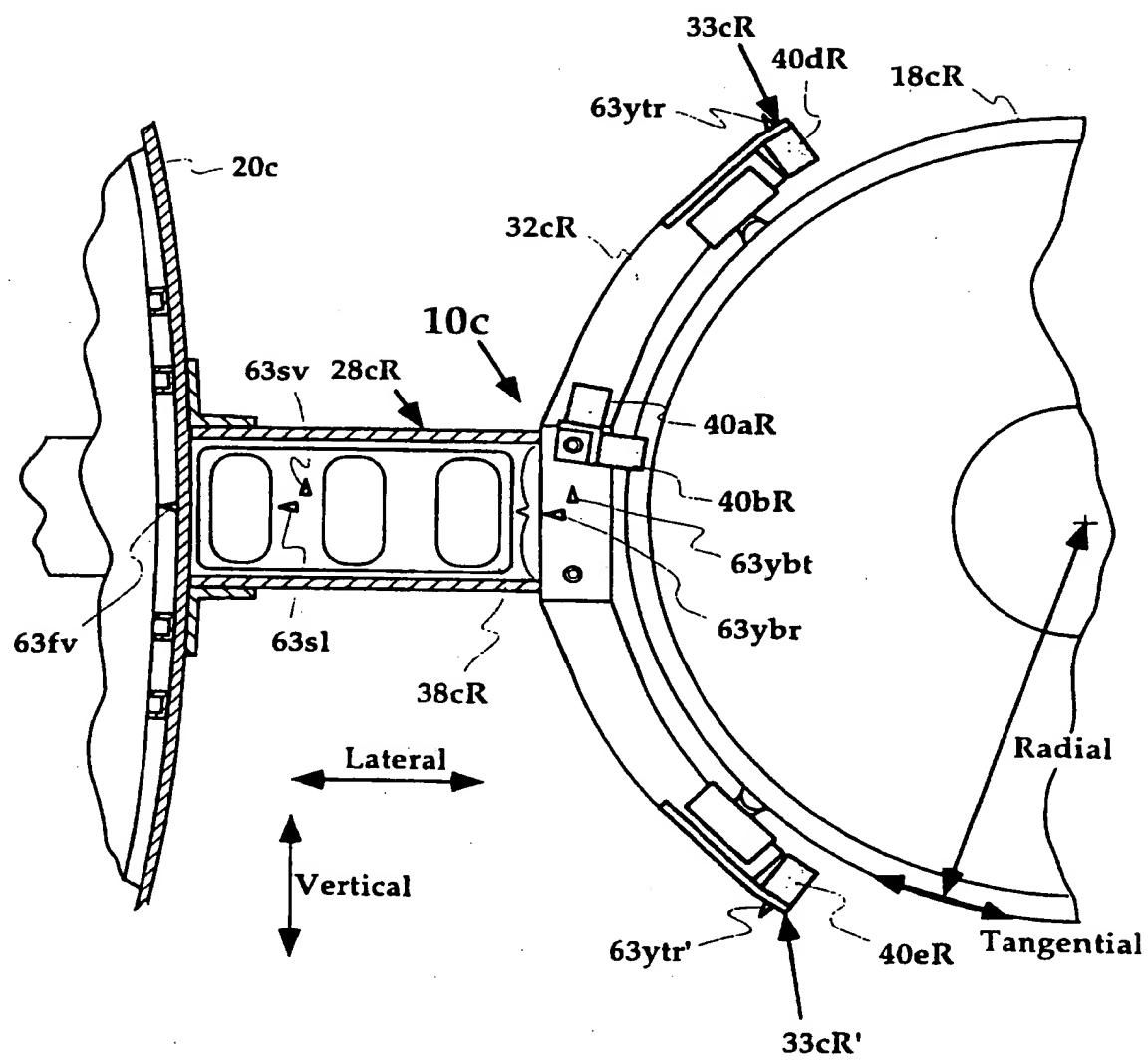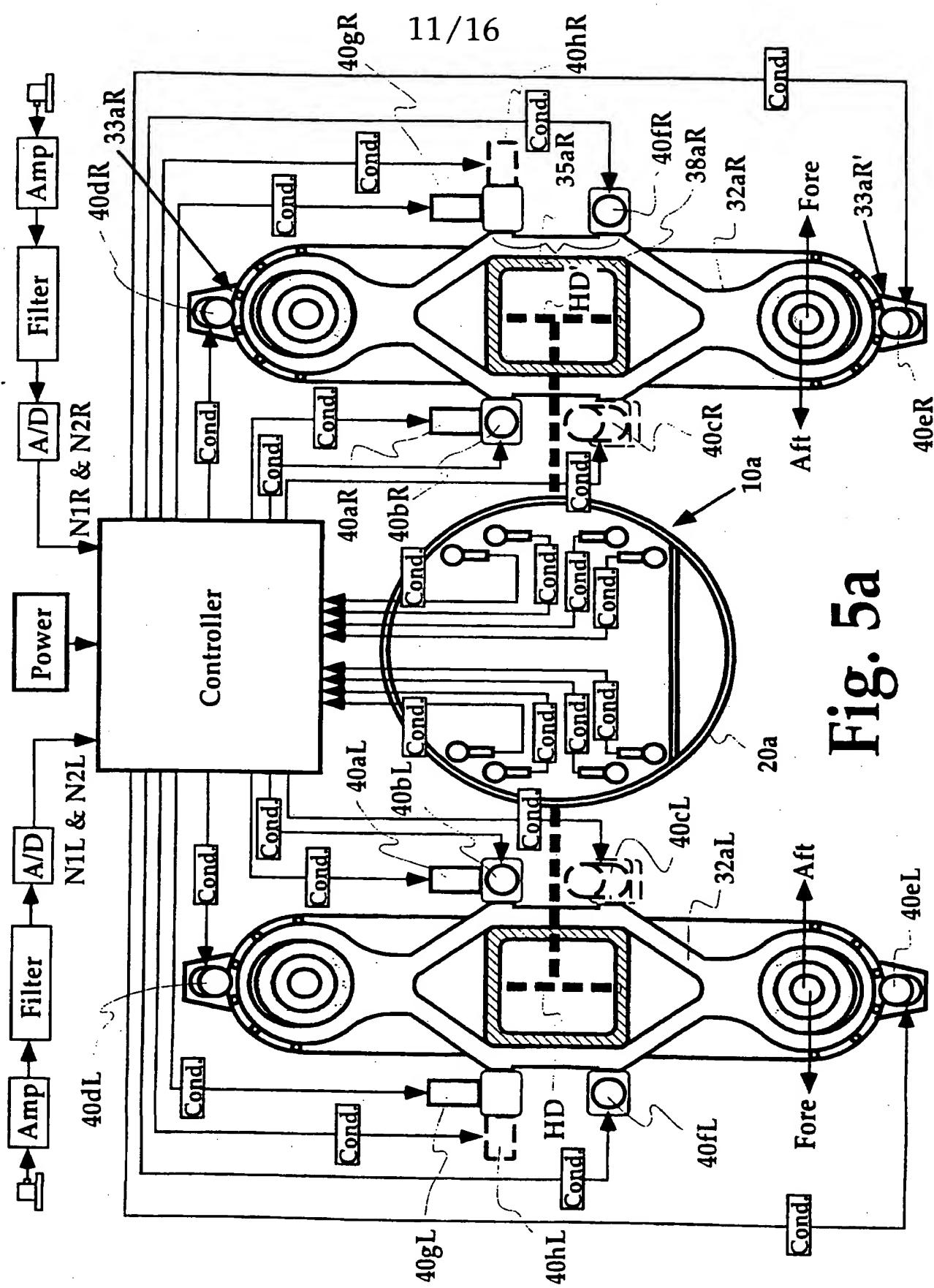
Fig. 4a

Fig. 4b

Fig. 5a

Fig. 5d

Fig. 5c

Fig. 5b

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Fig. 6a

Fig. 6b

15/16

Fig. 6c

Fig. 7a

Source — 18k

Ref Sensor — 50k

Limiter — 55k

PLL — 57k

Divide — 89k

Divide — 58k

94k

93k

95k

N1Rx256

Modulo Counter — 99k

Digital IO — 96k

Lookup Table — 97k 98k

N1R Control Filter — 13k

Update Means — 71k

C Model — 72k

Cond. — 11k

Output Transducer — 12k, 16k, 40k

Error Sensor — 44k

Cond. — 42k, 63k

10k

d

Fig. 7b

+Peak — 90k

-Peak — 91k

Fig. 7c

+V

-V — 92k

91k

Fig. 7d

Count

255

0

Cycle

1

2
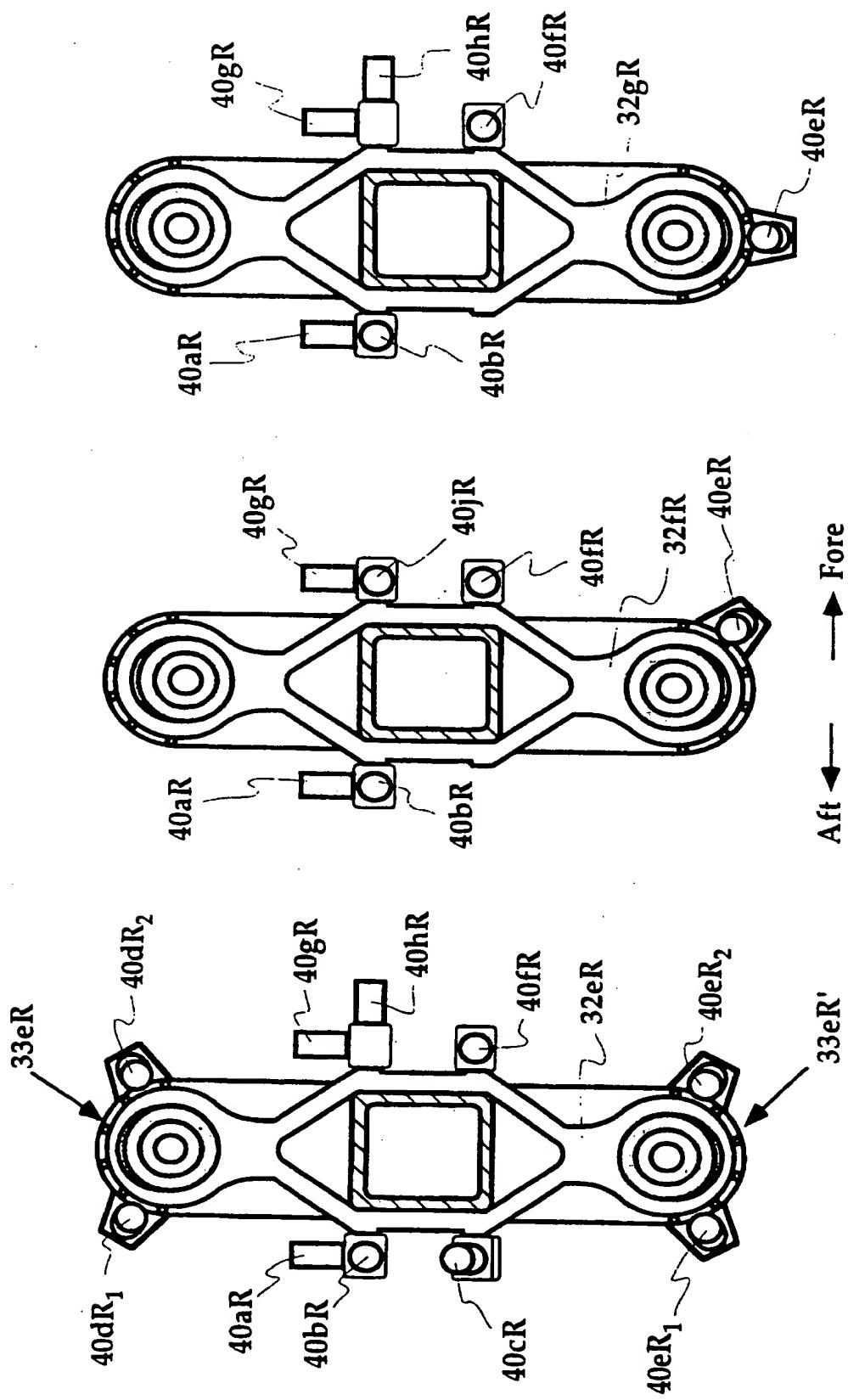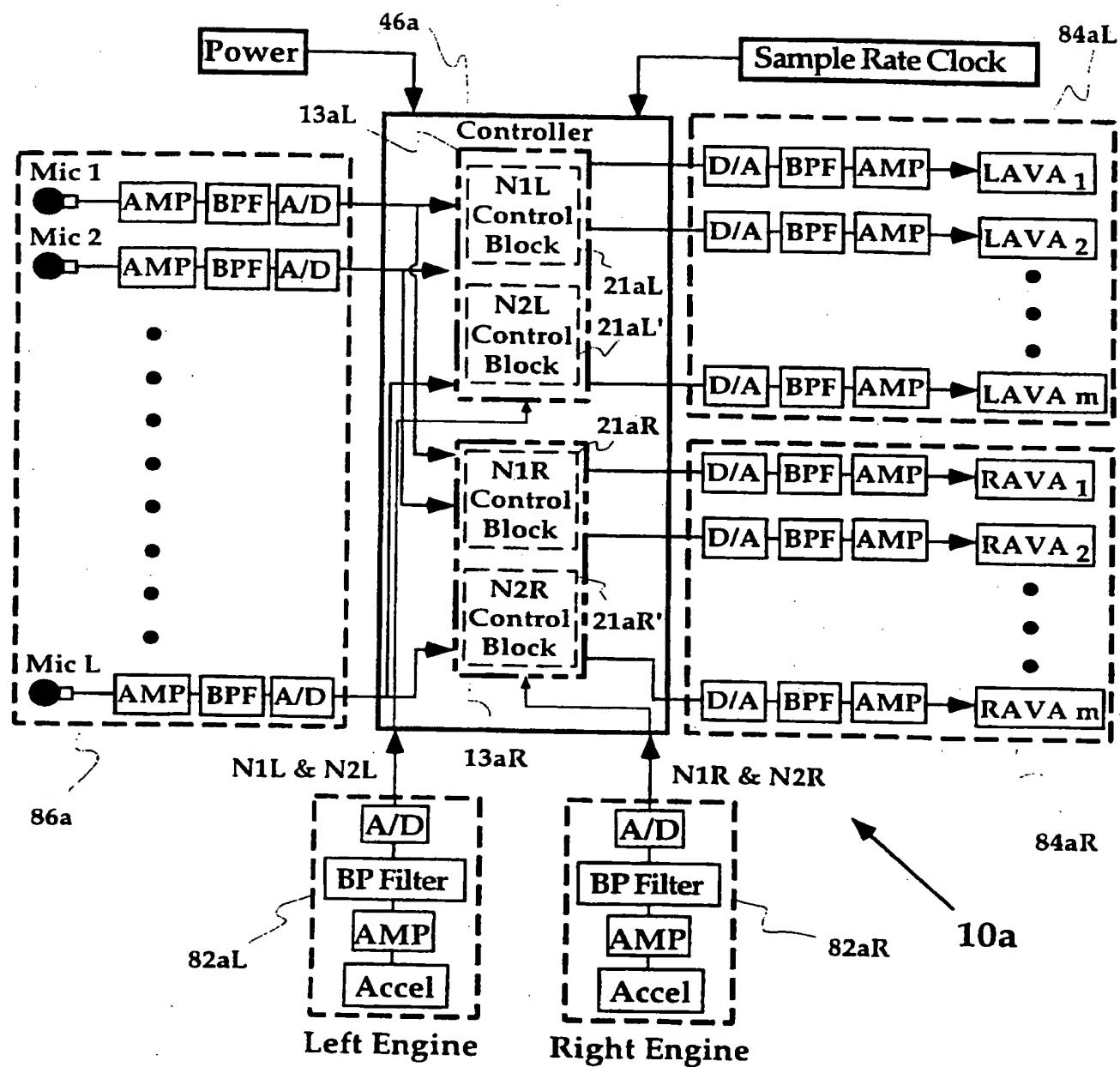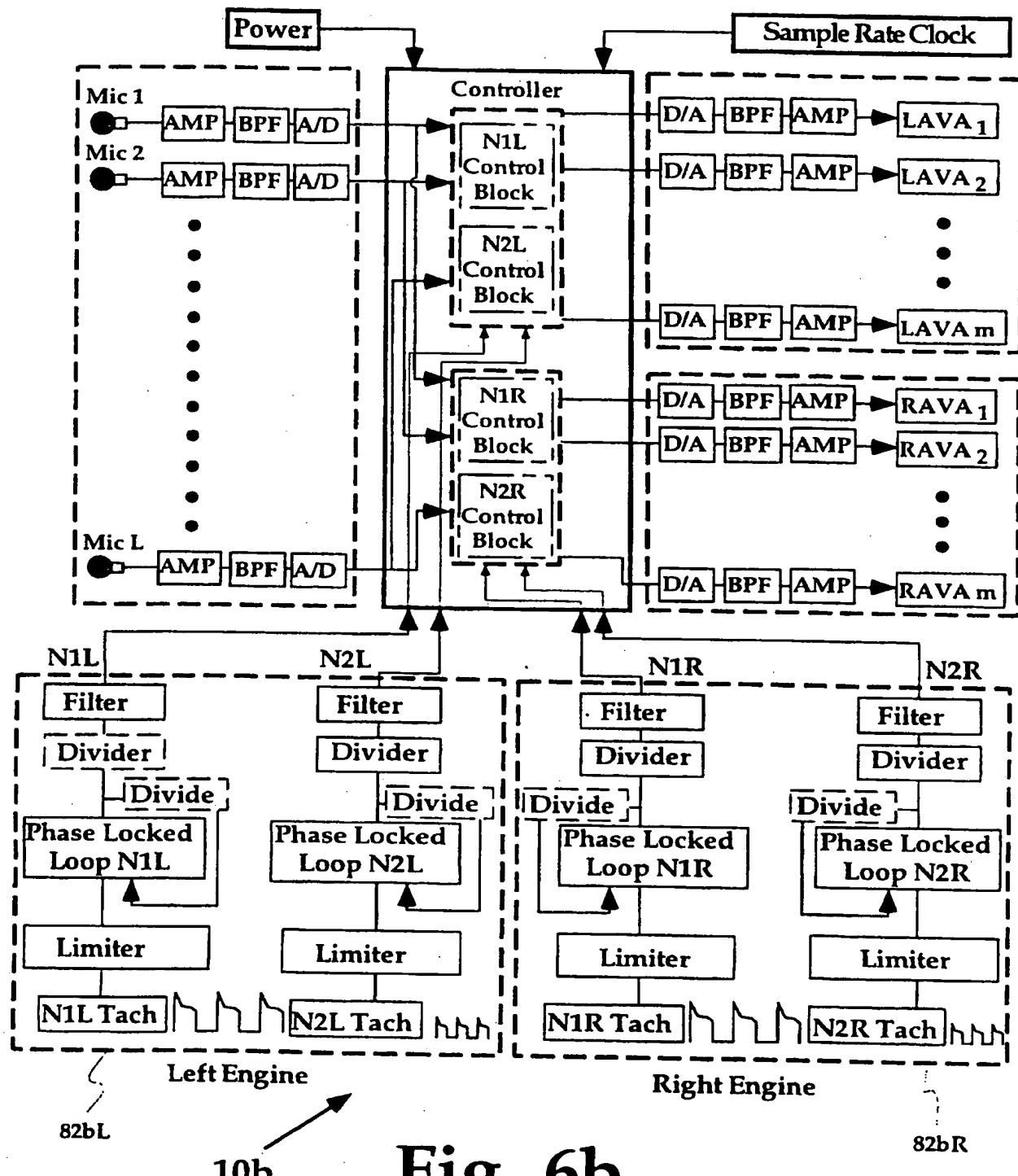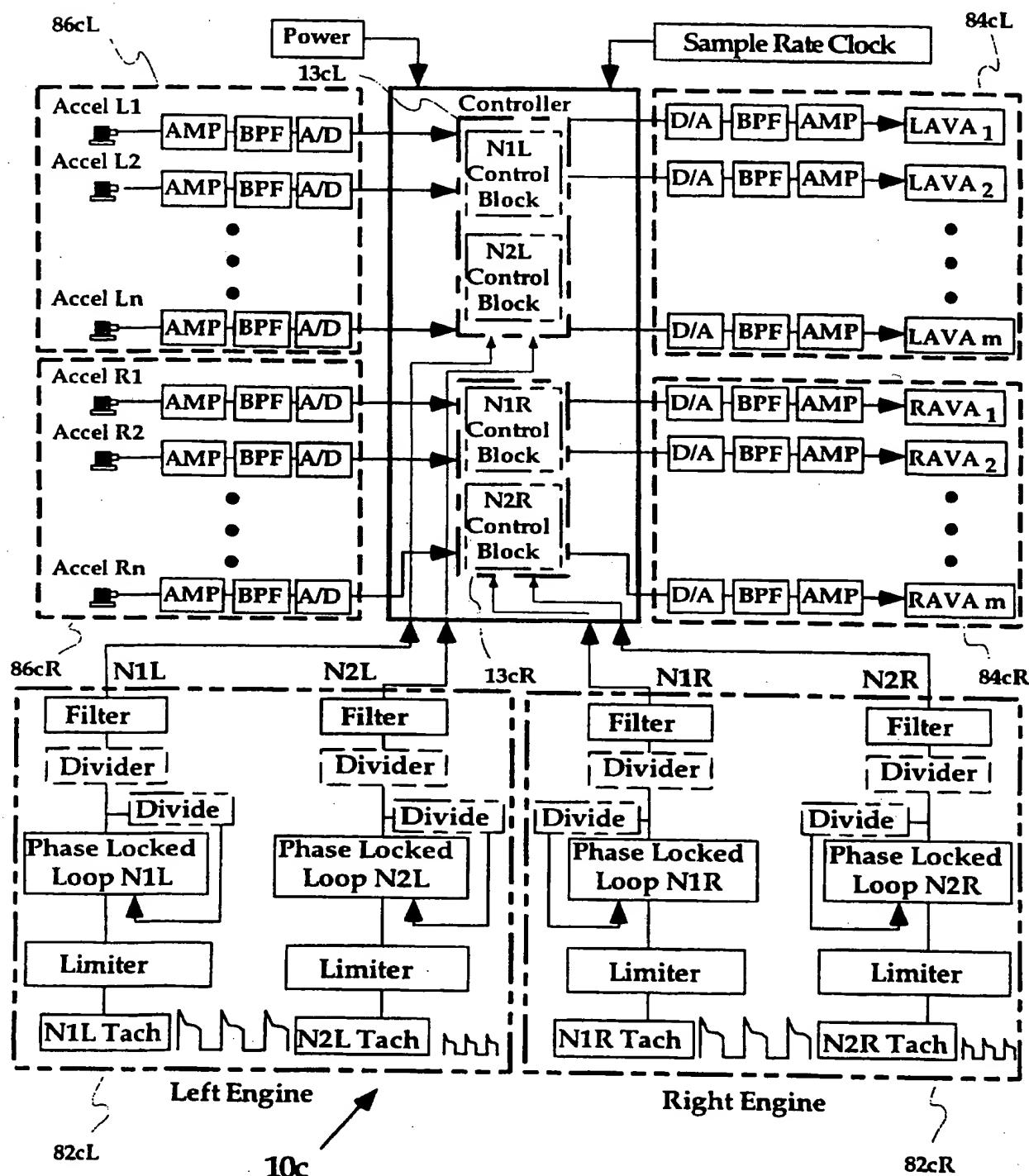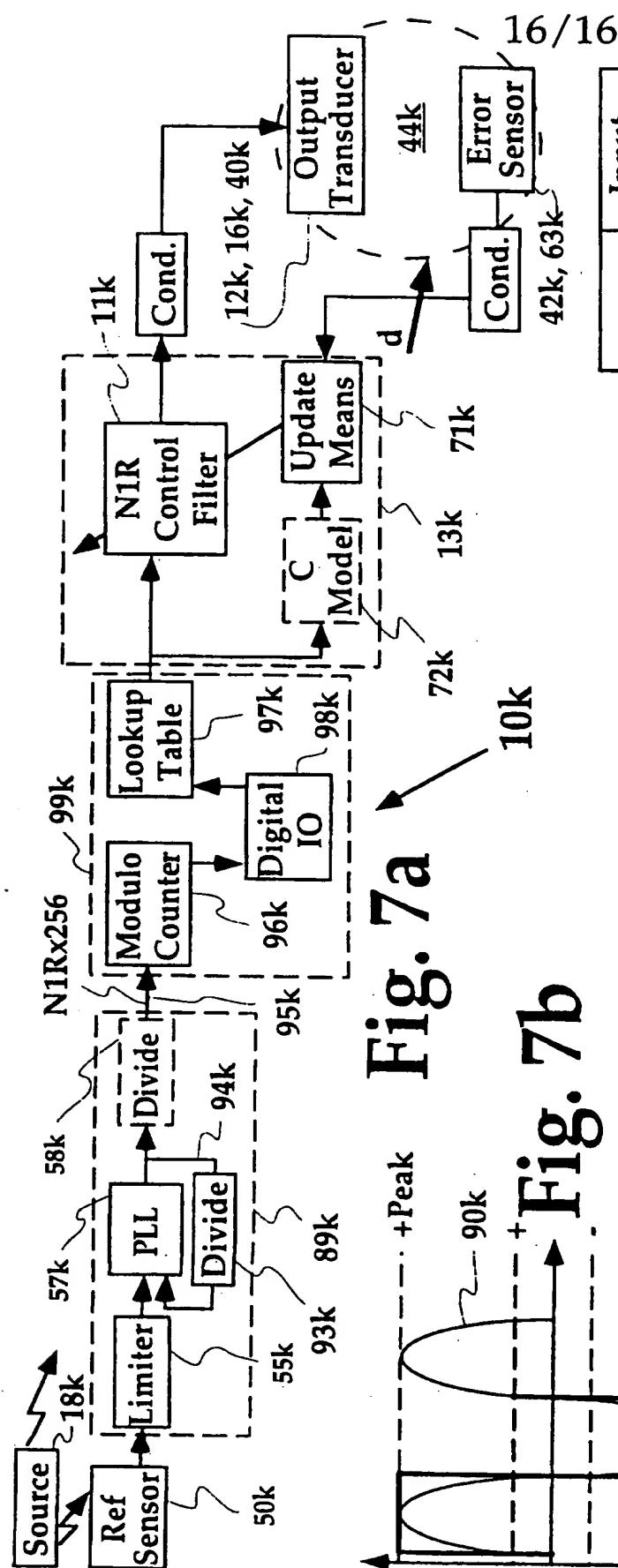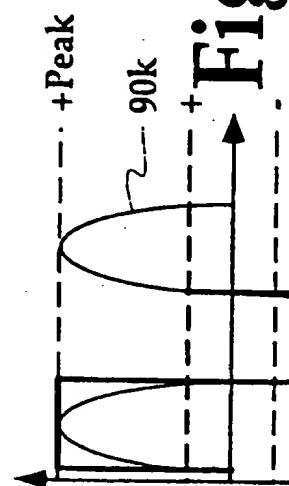
Fig. 7e

Count	Input Signal
0	0.0000
1	0.0245
2	0.0491
.	.
64	1.0000
.	.
128	0.0000
.	.
255	-0.0245
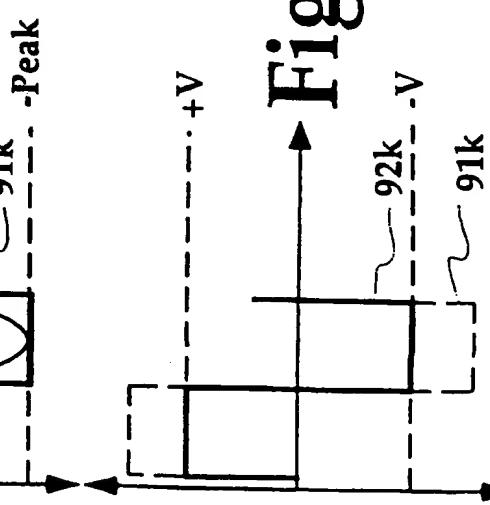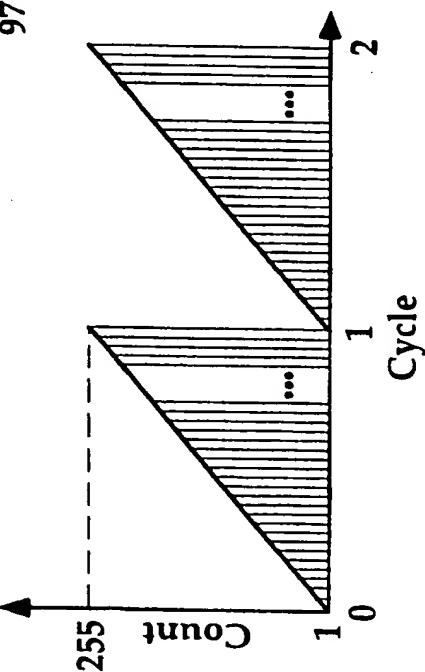
97k

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   G10K11/178

According to International Patent Classification(IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   G10K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document. with indication. where appropriate. of the relevant passages	Relevant to claim No.
X	US 5 515 444 A (BURDISSO RICARDO ET AL) 7 May 1996 see column 6, line 65 – column 7, line 55; figure 1	1-4,6,7, 11
Y		5,12,17, 19,22,23
Y	WO 95 34769 A (LORD CORP) 21 December 1995 cited in the application see page 2, line 18 – page 3, line 34	5,12,17, 19,22,23
A	US 5 423 658 A (PLA FREDERIC G ET AL) 13 June 1995 see column 3, line 30 – column 4, line 18	1-30
	–/--	

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of theinternational search	Date of mailing of the international search report
17 November 1997	21/11/1997

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INTERNATIONAL SEARCH REPORT

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 96 12121 A (LORD CORP ;SCHMIDT WARREN E (US); IVERS DOUGLAS E (US); JOLLY MARK) 25 April 1996 cited in the application ---	
A	US 5 386 689 A (BOZICH DANIEL J ET AL) 7 February 1995 -----	

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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